ELEMENTS

OF

ELECTRICITY, MAGNETISM,

AND

ELECTRO-DYNAMICS,

EMBRACING

THE LATEST DISCOVERIES AND IMPROVEMENTS,

DIGESTED INTO THE FORM OF A TREATISE,

FOR THE USE OF THE STUDENTS OF HARVARD UNIVERSITY;

BEING

THE SECOND PART

OF

A COURSE OF NATURAL PHILOSOPHY,

By JOHN FARRAR, LL. D.

AND

THE FIRST PART

OF

A NEW COURSE OF PHYSICS,

By JOSEPH LOVERING,

HOLLIS PROFESSOR OF MATHEMATICS AND NATURAL PHILOSOPHY IN HARVARD UNIVERSITY.

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ADVERTISEMENT.

I WAS induced to undertake the preparation and publication of this Treatise on Electricity, Magnetism, and Electro-Dynamics, at the request of my friend, JOHN FARRAR, LL. D. The time having arrived for another edition of the Second Part of the Cambridge Course of Natural Philosophy, he was anxious to have the remarkable discoveries of the last few years incorporated into it, so as to adapt it to the present state of these sciences: a task which his own feeble health did not permit him to engage in himself. It will be understood, therefore, that the book now offered to the public is based upon the old Treatise, with such changes as the growth of these sciences have rendered necessary. These alterations are very considerable, and of very great importance. The researches of Faraday and Becquerel upon the general subject, and the numerous discoveries and investigations in our own country and abroad on a smaller scale and in reference to departments only of the science, have produced such a revolution in it, that many parts of the old Treatise required to be entirely recast, and all demanded very material alterations. This has been my object in the following publication: and while endeavoring to present to the public a book that should embody all the important discoveries of our own times, I have tried to avoid unnecessary changes, or the introduction of points which, although new, were unsettled and hypothetical.

JOSEPH LOVERING.

CAMBRIDGE, June 17, 1842.

All the apparatus for illustrating the principles in Electro-Dynamics is neatly manufactured by DANIEL DAVIS, Jr., Cornhill, Boston: to whom I am under obligation for his promptness in furnishing me for my Plates with accurate drawings of the instruments, as they are made by him.

J. L.

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ELECTRICITY.

General Phenomena of Electrical Attraction and Repulsion; Conductors and Non-Conductors; two Kinds of Electricity.

1. The properties which we have hitherto discovered in bodies seem to be inherent in them, and permanently attached to the matter of which they are composed. Thus heavy bodies cannot be deprived of their gravity, nor their particles lose the property of mutual attraction.

We come now to consider certain transient states, or modifications, of which bodies are susceptible, and which are the more remarkable, since, without adding to their particles, or taking from them, any tangible or ponderable principle, they are notwithstanding attended with very powerful mechanical effects, which may be seen in the motion of material bodies.

For example, if we take a stick of sealing-wax, or a glass tube, or a piece of amber, which has been for a long time untouched, and bring it near some small pieces of paper, chaff, or other light substance, no impression is produced; but if we first rub lightly and briskly, the glass tube, the sealing-wax, or the amber, with a piece of dry woollen cloth, or cat skin, upon its being brought near either of the light substances above mentioned, a strong attraction will be manifest. We have here a new property or faculty developed by friction, and which did not previously exist. This property has been called *electricity*, from the Greek word ἤλεκτρον, which signifies *amber*, this being the substance in which it was first observed.

Several centuries passed without any thing being known beyond the simple fact just stated; but for the last eighty years the pheno-

mena have been more carefully examined, and have thus led to the discovery of many important results, which together form one of the most interesting parts of natural philosophy.

The first step to be taken, is to study carefully the fundamental phenomenon above described, and to examine all the various circumstances under which it presents itself. By rubbing tubes of glass, sulphur, or sealing-wax, of considerable size, an inch in diameter, for example, and a foot long, light bodies are attracted from a distance; and they are seen to rush with great rapidity against the electrified tube. Some adhere to it; others, upon coming in contact with it, are immediately repelled. If the tube be brought near the hand or the face, at a certain distance a sensation is felt similar to that produced by a cobweb; and if it be touched with the finger or a metallic ball, a spark darts with a crackling noise from the tube to the body presented to it. When the experiment is performed in the dark, this spark becomes vivid, and we constantly observe a bluish light following the rubber as it passes along the tube. The effect may be still further increased, by substituting for the tube a large globe, or cylinder, or plate, fixed between two cushions, and made to turn by means of a handle. This apparatus is called an *electrical machine*. It is ordinarily accompanied with other appendages, which render its effects much more certain and intense; of these we shall speak hereafter, when we have treated of the theoretical principles on which they depend. In the mean time, the apparatus, such as we have described it, is sufficient to establish the fundamental phenomena which we have stated.

It may now be asked, what is the nature of the principle under consideration? how does it exist in bodies? how is its action developed by friction? These questions we are unable to answer; but whatever be the cause of the phenomena in question, to avoid circumlocution we shall call it *electricity*, just as we give the name of *caloric* to the unknown principle of heat.

All vitreous and resinous substances are capable of exhibiting the phenomena above mentioned in different degrees. Silks also answer the same purpose; but if we take a metallic tube and rub it with a cat skin or a piece of woollen cloth, it will present no luminous appearance, it will excite no sensation, nor manifest any disposition to attract light bodies.

2. If, however, instead of taking the metallic tube in the hand, we hold it by means of a tube of glass or resin, and rub it as before without its touching any other substance but the rubber, it will acquire all the electric properties of glass or amber. The same phenomena occur, also, if instead of the glass or resinous handle, we make use of a silk holder, consisting of several thicknesses, or if we suspend the metallic tube by means of silk cords. The electric properties will continue, however, only while the tube has no other communication with surrounding bodies; for if we touch it with the finger or with another piece of metal, all signs of electricity instantly vanish.

It is evident from these experiments, that if the metal did not at first acquire electric properties by friction, it was not because it was incapable of receiving them; but because it could not retain them; for when it is made to possess them, it may be deprived of them immediately by touching it with the finger or with another piece of metal. Thus when it is held in the hand and rubbed, the electricity is dissipated as fast as it is developed. We must not, therefore, be surprised that no effect is produced. But the electricity becomes sensible when the metal is suspended in the air by means of glass, resin, or silk. We infer, therefore, that these substances resist the passage of electricity; we know, moreover, directly, that electricity does not readily pass along a silk riband, a glass tube, or a stick of resin; for when one of these substances is rendered electrical by friction, if we touch one part, we deprive this of its electric properties without affecting the rest. On this account, we can electrify bodies of the above description by friction, while holding them in the hand, but not those of a metallic nature.

We are thus led to distinguish natural bodies into two great classes, according as they do or do not transmit the electric principle, and which are hence called *conductors* and *non-conductors*; the latter are also called *insulating bodies*, because, when they are employed as supports, they serve to cut off all communication between a conducting body and other conductors which might deprive it of its electricity.*

* Formerly, non-conducting bodies were called *electrics per se*, or *idio-electrics*, that is, self-electrical; and conductors were called *anelectrics* or non-elec-

The atmosphere is evidently of the class of con-conducting bodies; since, if it afforded a free passage to electricity, no body surrounded by it could exhibit durable electrical phenomena. Now a tube of glass or resin, being rubbed, preserves its electric properties for a considerable time, although immersed in this fluid.

Water, on the other hand, is a conductor; for if we moisten with this liquid or only with its vapour, a tube of glass or resin, electrified by friction, it immediately loses all its virtue. Thus the aqueous vapour suspended in the air impairs the insulating properties of this fluid, and it is for this reason that electrical experiments succeed best in cold and dry weather, because then there is less vapour contained in the atmosphere.

This difference in the disposition of different bodies to retain and transmit electricity, was first made known by Grey. He owed the discovery to accident, but to an accident of which he well knew how to avail himself.

The distribution of all bodies into two great classes of conductors and non-conductors, like most other systematic classifications in physical science, is not in strict conformity with the natural properties of material substances; and though such a distinction is useful and necessary, it must be adopted subject to a clear knowledge of the restrictions under which only it can be applied. Few bodies can be found which, in a strict sense, belong to either of the specified classes; and many exist which present nearly equal claims to be placed under either of them. There is, in fact, no substance whose surface is strictly impassable by the electric fluid, though there are many which offer such obstruction to its propagation over them, that, in a practical sense, they may be regarded as non-conductors. It is equally impossible to find any body whose surface offers so free a passage to the electric fluid, that under no conceivable circumstance is any the least obstruction discoverable; but there are many which offer an obstruction so small in amount, that they may be, and are, regarded as practically

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trics, because it was believed that the first only could be electrified by friction. This was an error. All bodies become electrical by being rubbed, but all are not capable of retaining the electricity thus developed, without being insulated.

perfect conductors. Finally, there are many substances which possess the conducting power so imperfectly, that it seems doubtful to which class they should most properly be assigned. There is, in a word, a progression of degrees in which the conducting power is found in bodies; and the various substances in nature might be tabulated or arranged in a series, beginning with that substance over which electricity passes most freely, proceeding through gradations to those substances which offer such obstruction to its passage as scarcely to be considered as conductors, and from these through the catalogue of bodies offering more and more obstruction to its transmission, until we arrive at that substance which approaches nearest to an absolute non-conductor. In the formation of such a series, however, much difficulty is found, owing partly to the absence of any precise measure of the conducting power of bodies, and partly to the fact that the conducting power of the same body at different times is subject to variations, proceeding from causes external to it; such as its hygrometric state, or its temperature.

Of all known substances, those which offer least obstruction to the passage of electricity are the metals. These bodies all appear to transmit common electricity without sensible obstruction: but, from experiments made with galvanic electricity, there is reason to think that even the metals are permeable in different degrees by the electric fluid.

Mr. Singer, so well known for his investigations in electricity, observes, that a tendency of the electric fluid to pass through good conductors offers a measure of their conducting power: for if various substances of the same length and magnitude are used simultaneously to connect an electrified conductor with one not electrified, that through which the fluid passes in preference to the others is the best conductor; or if they are placed in succession, that which conveys the charge most completely may be considered the most perfect. Metals, although the most perfect of known conductors, offer some slight resistance to the transmission of electricity; and a charge will even prefer a short passage through air to a current of twenty or thirty feet along thin wire.

According to the experiments of M. Achard, of Berlin, ice whose temperature is below 13° Fahr. is a non-conductor, though at all higher temperatures it is a conductor. That philoso-

pher experimented on a rod of ice two feet long and two inches in diameter, and found that at 18° Fahr. it became an imperfect conductor, and that at 13° it ceased to have any discoverable conducting power whatever.

Since the best test of a non-conductor is to ascertain whether electricity can be excited on its surface so as to remain on it, M. Achard, having frozen some water so as to exclude all air-bubbles from it, formed it into a spheroid, and mounted it on an axis. When the temperature of this was reduced below 13°, he was able to excite upon it a very high degree of electricity by the ordinary process.

It is doubtful whether rarefied air should occupy a place among conducting bodies, for the manner in which it admits the motion of electricity is probably very different from that in which other conducting substances exert that power. It will hereafter appear that the electric fluid is retained on the surfaces of electrified bodies by the atmospheric pressure, and that when its tension exceeds this pressure it escapes spontaneously. Whatever, therefore, be the intensity of the electric fluid on any electrified body, if the atmosphere surrounding it is so rarefied that its pressure shall be less than that tension, the electricity must escape by its self-expansive power; and, in this sense, the surrounding air thus rarefied may be regarded as a conductor. Various experiments have been made to ascertain whether a vacuum is or is not a non-conductor; and, although the question cannot be considered as finally settled, there appears every reason from analogy to consider it a perfect conductor.

In conformity with the usage of all writers on this branch of physics, we have adopted, and shall continue to use, the term *conducting power* to express that quality of bodies in virtue of which they afford a free passage to electricity. It were, however, to be wished that this property had been designated by some term which would more correctly express what appears, from observation and experiment, to be its nature. Experiment seems to prove that the particles of bodies have no peculiar affinity for the free electric fluid, and they neither attract nor repel it. So far, therefore, as the phrase conducting power implies an *active* quality in relation to that fluid, it does not correctly express the property to which it is

applied. A conductor exercises no action on the electric fluid, and is merely characterised by the negative or passive condition of offering no obstruction to its motion. The electric fluid, being self-expansive, has a natural tendency to diffuse itself into the surrounding space; and when, in virtue of this elasticity, it passes from the surface of one conductor to the surface of another, the effect is analogous to that which takes place when a vessel filled with common air is put into communication with another vessel in which there is a vacuum. The air, by its elasticity, expands and diffuses itself through the dimensions of the two vessels, having before been confined to one of them. What the vacuum is to a vessel filled with air, a conductor in its natural state is to an electrified conductor. We do not wish, however, to be understood to state that, when an electrified conductor is brought into contact with another conductor not electrified, the electric fluid diffuses itself over both conductors *according to the same law* as air would distribute itself between the two receivers just referred to. It *does*, however, diffuse itself over both conductors according to its own peculiar laws.

The physical condition which confers on bodies this conducting power has been a subject of fruitless inquiry among electricians. All that is known respecting it is, that the conducting quality depends partly, if not altogether, on the peculiar arrangement of the particles of bodies, and is not dependent on the particles themselves. It has been ascertained, that all bodies become conductors in a state of solution.

It is natural to inquire whether any relation exists between the power of conducting electricity and other imponderable physical influences, such as light and heat. There is, however, one obvious distinction to be observed between the manner in which light and heat are transmitted through bodies, and that in which electricity is transmitted by them. If a body be capable of conducting or transmitting light, that fluid will pass through its solid dimensions; thus glass, water, air, and other transparent bodies, allow light to pass through them; in other words, they are conductors of light, while the metals generally, and other opaque substances, refuse to admit light through their dimensions, and either reflect it from their surfaces or absorb it upon them. The metals in general are free conductors of heat: if one end of a metallic bar be heated, the heat

soon passes through all its dimensions, and the temperature of the other end rises. But, on the other hand, glass and water, which are such perfect conductors of light, scarcely possess the power of conducting heat at all: one end of a rod of glass may be rendered white hot, while no sensible elevation of temperature takes place at the other end.

Electricity, however, is transmitted or excited not through the interior dimensions of bodies, but only on their surfaces; and the conducting power, therefore, belongs solely to the surface. No relation exists between the conductors of heat or light and those of electricity. Glass, which is almost a perfect conductor of light, is a non-conductor of heat, and also of electricity. Sealing-wax, which is an opaque substance, and therefore a non-conductor of light, is likewise a non-conductor of heat and electricity. The metals, on the other hand, which are non-conductors of light, are conductors of both heat and electricity. Water is a conductor of electricity and light, but a non-conductor of heat.

There is no constant relation between the state of bodies and their conducting power. Among solid bodies, the metals transmit electricity readily, dry gums and resins scarcely transmit it at all. Almost all liquids are good conductors; oil, however, is a very imperfect conductor. Wax and tallow, when cold, conduct badly; when melted, they conduct well. The power of conducting electricity is observed in the most opposite states; for example, in the flame of alcohol and in ice. The temperature of bodies seems to have no sensible influence on the electric sparks which proceed from them. Those which proceed from ice are not cold, and those which proceed from red-hot iron, do not appear to have their heat increased.

The air and dry gases, besides their insulating property, seem also to have the faculty of confining electricity upon the surface of bodies by the force of pressure. For, if we place under the receiver of an air-pump, a conducting body electrified and insulated upon supporters of glass or resin, this body, when the air is rarefied to a certain degree, loses all its electricity, which shoots off with a bluish light towards the conducting bodies by which it may communicate with the ground. If we place under the same circumstances, a non-conducting body, a stick of sealing wax, for exam-

ple, electrified by friction, the electricity abandons it also as soon as a vacuum is produced, but more slowly than in the case of a conducting body, and with a sensible interval of time. These phenomena, therefore, seem to indicate that the electricity is retained upon the surface of conducting bodies only by the pressure of the air; and that at the surface of non-conducting bodies, as dry glass and resin, it is retained by this pressure, joined to the difficulty which it meets with in disengaging itself from their particles.

The conducting property of the metals is advantageously employed to facilitate the operation of the electrical machine. We suspend by silk cords, or place upon glass cylinders, a metallic bar one side or one end of which is brought very near the globe or plate, which is electrified by friction. Then, as the electricity is developed, it passes to this insulated metallic conductor, and is retained there. If we touch this *prime conductor*, as it is called, with another metallic bar insulated in the same way, this second bar becomes electrical also, and the electricity may thus be transferred wherever we please. It is of little importance at what point we touch the prime conductor; it will give its electricity from any part. If we attach to it a metallic wire of any length, as a thousand yards, for example, this wire will also become almost instantaneously electrical through its whole extent, provided it is equally insulated in every part. We may also continue the communication through portions of water, in a fluid state, contained and insulated in vessels of glass. These are the consequences and the proofs of the free passage which conducting bodies offer to electricity.

To insure success in our experiments, it is necessary that the silk cords or glass tubes which serve to insulate conductors, should be very dry; otherwise the electric properties grow weaker and weaker, and soon cease entirely. Very fine dry silk thread forms an excellent insulator for light bodies. If we suspend to a thread of this description, a small ball of elder pith, which is extremely light and a good conductor at the same time, we shall have a very simple and convenient instrument for studying the theory of electricity. This little pendulous body is usually attached to a movable stand, as in figure 1. Fig. 1.

3. If the pith ball is brought in contact with an electrified glass

tube, and is then separated without being touched, it will be found to have acquired electric properties. It will attract chaff, dust, and other light substances which are presented to it. It will be drawn toward the hand if placed near it; in a word, it has been electrified *by communication.*

When the air is dry, these properties will continue a considerable time, provided the ball remain unconnected with any conducting substance; but if it be touched, it will immediately return to its natural state, and its electricity disappear.

4. Here, as in the case of the electrified conductor, it may be asked what becomes of the electricity, and why does it produce no effect? The following experiment will enable us to answer these questions.

If, instead of touching the ball with the finger, we touch it with another ball, eighty or a hundred times as large, suspended in the same way, we shall find that the first has lost its electric virtue almost as completely as if it had been touched with the finger. We thus perceive that a given quantity of electricity loses in intensity by being distributed over a larger surface; for the interior of the balls has no effect, and whether they be empty or full, the phenomenon takes place in the same way. After this, it will be readily understood that the little ball loses its electric virtue, by dividing it with the human body and the immense mass of the earth, which are conducting bodies communicating with it. It is on this account that we often call the earth the *common reservoir* of electricity.

5. Let us now examine more carefully what takes place when we bring the pith ball toward the electrified tube. At first it is attracted by the tube, and adheres to its surface; but after a short interval, just sufficient for the electricity of the tube to be communicated, it is repelled and seems to fly off as long as it preserves its electricity. By bringing the tube, however, very suddenly near the ball, we sometimes make the ball return, and thus change its repulsion into attraction; this is a compound phenomenon, the cause of which we shall explain hereafter; but confining ourselves for the present to what takes place when the tube is presented to the ball from a distance, for the purpose of foretelling its motions after a part of the electricity has been communicated to it, we see

that it always begins with flying from the tube. Hence we derive this important conclusion, that with the exception of certain particular cases, the cause of which remains to be explained, bodies electrified by communication, mutually repel each other.

It would at first seem that the preceding experiment did not fully authorize this conclusion. We indeed see that the ball flies from the tube, whose electricity it has shared, but it does not appear that the tube flies from the ball. The sole cause of this however is, that it is too heavy. The ball only is displaced, not being sufficient to move the tube; but to present the subject fairly, we take two equal pith balls, and attach them to the two extremities of a linen thread, which is a conductor; we next suspend this thread from its middle point by a thread of silk, as represented in figure 2; Fig. 2. then the two balls will communicate by the linen thread and the silk thread will insulate them both. Now if we touch the two balls, or only one of them, with an electrified tube, we shall see that they will not only fly from the tube whose electricity they have shared, but from each other, and the two parts of the thread will diverge, as represented in figure 3. Fig. 3.

6. The repulsion of the little electrified ball takes place equally, whatever be the nature of the tube which is employed to give it electricity, provided that it be always the same tube that is afterwards presented to it. But if after having communicated to it the electricity of a glass tube rubbed with woollen, we bring toward it a tube of sulphur or resin, rubbed with the same substance, instead of flying from this second tube, it will approach it, and rush with more force than it would do, if it had not been previously electrified. The same thing happens if we begin by electrifying the ball with the resinous tube, and afterward bring toward it the tube of glass; attraction takes place equally in each case.

We find, therefore, that when a body has been electrified and insulated like the little pendulum above referred to, other electrified bodies which are brought near it, do not all act upon it in the same manner, since some repel and others attract it. We are hence led to distinguish electricity into two kinds, the one analogous to that produced by glass, when rubbed with woollen, and which we shall call *vitreous electricity*; the other similar to that produced by resin, rubbed also with woollen, and which we shall call *resin-*

ous electricity. This important distinction was first observed by Dufay.

All the phenomena, then, of attraction and repulsion which we have thus far observed may be expressed by this very simple law; *bodies charged wih electricity of the same kind mutually repel each other; but when they are charged with different electricities they attract each other.*

Although this proposition seems to be purely the enunciation of facts, yet we must not attach to it the idea of absolute reality; for motions perfectly similar to those presented by electrified bodies may be produced without any real attraction or repulsion among the material particles. For example, imagine a glass vessel AA'
Fig. 4. filled with a heavy fluid, as water or mercury, and suspended vertically by a cord from a fixed point S. If this vessel be not touched, it will remain at rest in virtue of the laws of equilibrium,
Mech. 451. and the fluid which it contains will give it no horizontal motion, because the lateral pressures, exerted at the same depth in the opposite directions AB, $B'A'$, are equal to each other. But suppose that with a burning mirror MM we direct a cone of light upon the point A, and thus cause a small hole in the side of the vessel at this point; then the fluid flowing freely through this hole, the pressure in the direction BA will become nothing, and the pressure in the direction AB having nothing to counterbalance it, the vessel will recede from the mirror as if a repulsive force were exerted between them. On the contrary, if the focus of the cone were directed to the point A' through the matter of the vessel, the fluid being supposed to be transparent, the vessel will approach the mirror as if it were urged by an attractive force. Still there is no absolute attraction or repulsion; the motion observed is the simple effect of the proper hydrostatic pressure of the fluid contained in the vessel AA'. Now this ought not only to put us on our guard against admitting the idea of a real attraction or repulsion between the material particles of electrified bodies; but we shall see by and by, that the motions of these bodies are produced by a precisely similar mechanical action; for their material particles, although electrified, do not acquire any real influence over each other; what takes place is effected by the vitreous and resinous electricitise which cover them, and whose reciprocal action is confined to aug-

menting or diminishing, upon certain parts of their surfaces, the pressure exerted there by the electricity against the surrounding air which retains it, or in general against the obstacles which oppose its change of place. After what is now laid down, if we continue to employ the words attraction and repulsion to denote the motions of electrified bodies, the terms are to be considered as expressing simply the circumstances of these motions, and not as indicating the real cause on which they depend.

The attraction and repulsion under consideration take place not only through the air; they are exerted also through other non-conducting bodies, as glass and resin. If we suspend within a glass phial a stick of sealing wax rubbed and electrified, it attracts light bodies situated without the phial, just as if there were nothing interposed. This transmission manifests itself also through conducting bodies; but it is disguised under another phenomenon, of which we shall speak hereafter.

To discover whether a given substance, on being rubbed in a certain manner, acquires the vitreous or resinous electricity, we must observe the effect it produces upon the electrical pendulum previously charged with a known electricity. For example, we touch this pendulum with a glass tube rubbed with woollen cloth; and it receives the vitreous electricity. We rub with the same substance the body whose electricity is to be tried, and bring it toward the ball of the pendulum. If it repels the ball, its electricity is vitreous, if the ball is attracted, the electricity is resinous. We may vary the experiment if we choose, by first giving to the pendulous body the resinous electricity.

As the signs of electricity in certain cases are very feeble, it becomes desirable to increase the sensibility of the apparatus. This is affected by reducing the size of the pith-ball, and suspending it by a fine silk thread. If we use, for example, one of the original fibres, as they proceed from the silk worm, and not less than 10 or 12 inches in length, a very weak electricity will be sufficient to put it in motion. There are still more sensible instruments, with which we shall become acquainted as we proceed, and by means of which we shall be able to comprehend the most delicate phenomena; but the one above described will answer our purpose for the present.

By subjecting to this proof a great variety of bodies, rubbed

with different substances, we shall find that there is no constancy as to the kind of electricity developed, but that this depends as much on the nature of the rubbing substance, as on that of the body rubbed. Polished glass, for example, rubbed with woollen, acquires, as we have before said, the vitreous electricity; but when rubbed with a cat skin, it takes the resinous electricity. Silk rubbed with resin, exhibits the vitreous electricity; rubbed with polished glass, it acquires the resinous electricity.

The several substances of the subjoined table take the vitreous electricity when rubbed respectively with the substances following; and the resinous when rubbed with those which precede;

Cat skin,	Paper,
Polished glass,	Silk,
Woollen cloth,	Gum lac,
Feathers,	Rough glass,
Wood.	

It will hence be seen, that there is apparently no connexion between the nature of the substance and the kind of electricity produced by it.

The only general law which is known to exist among these phenomena, is, that *the rubbing body and the body rubbed always take different electricities; if the one be resinous, the other is vitreous, and* vice versâ.

To ascertain this in any particular case, we must insulate the two bodies which are to be rubbed against each other. If they are solid, we fit to them handles of glass or resin, by which they may be held. It is well when it is possible, to give to the substances rubbed the form of plates, that the friction may take place over a greater surface. We may insulate and try in the same way a solid body and pieces of cloth, fur, &c., or two substances of the latter kind only, &c. When we have continued the friction for a short time, we separate the two bodies; and holding them always by the insulating handle, we present them successively to a very sensible electrical pendulum, charged with a known kind of electricity. We shall then find in every case that one of the substances attracts and the other repels the pendulous body; the electricities are therefore dif-

ferent. Numerous experiments have been made to discover what are the circumstances which determine a body to take the particular kind of electricity which it is found to possess, but without making known any thing very decisive. Sometimes the result is apparently determined by the most trifling circumstance; when, for example, a piece of polished glass is rubbed against a piece of rough glass, the first takes the vitreous electricity, and the second the resinous, without any one being able to tell why the polishing of the surface should have this effect. If two ribands of white silk, taken from the same piece, are rubbed against each other crosswise, that which is rubbed transversely, acquires the resinous electricity, and that which is rubbed longitudinally, takes the vitreous electricity. Nothing further is known as to the effect of the direction of friction. Indeed, the result is not always the same with the same bodies. Æpinus assures us that he has observed this fact in rubbing a plate of copper with one of sulphur, and also in rubbing two squares of glass against each other; when separated, they were always in contrary states of electricity, but the same kind of electricity belonged sometimes to one and sometimes to the other.

From these phenomena, we are led to the following curious experiment. Two persons are placed upon stools, called *insulators*, the feet of which are of solid glass or other insulating substance. One holds in his hand a dry cat skin, and with it rubs or strikes the clothes of the other, and thus acquires himself the vitreous electricity, while he gives to the other the resinous electricity, as may be proved by bringing near them successively, an electrical pendulum charged with a known kind of electricity. If a person not insulated touches the persons electrified, he will draw a spark from each of them. It is evident that these phenomena can take place only while the electrified persons remain upon the insulating stool; for if they leave it, they immediately impart their electricity to the earth. It is on this account, that when we insulate only one of the persons, whether it be the one that rubs, or the one that is rubbed, the insulated person only shows signs of electricity; and if neither is insulated, no signs whatever are produced. It is manifest, moreover, that they

ought to touch or communicate with each other only through the rubber.

A cat skin is very convenient for this and many similar experiments, since it is very easily electrified. By passing the hand, in dry weather, over the back of a live cat, the hair stands erect, and is attracted to the hand; sometimes, indeed, we even hear a crackling noise, and obtain small sparks. This takes place only in cold weather, when the air is a good non-conductor. Dry hair is very easily electrified by friction, especially if it is fine and soft.

Electricity is also produced by the friction of liquids against solids. To prove this, we place upon an air pump a cylindrical glass receiver, to the upper extremity of which is fitted a wooden cup, containing a small quantity of mercury. The receiver is then exhausted, and the mercury, being pressed by the external air, filters through the pores of the wood, and falls in a fine shower, which strikes against the sides of the glass cylinder. If we now present the electrical pendulum, suspended by its silk thread, we shall find that the part thus rubbed, is electrified. The cylinder should be perfectly dry, in order that it may retain all its electricity, which is sufficiently feeble, when developed in this way, by the friction of falling mercury.

We are hence able to account for an appearance often noticed in barometers which are well freed from air. Upon being inclined in such a manner as to fill suddenly all the empty part of the tube, if the experiment is performed in the dark, a faint light is instantly seen, similar to that produced by a continued current of electricity through a vacuum.

We may also obtain electricity by the friction of a gas against a solid body. If a current of atmospheric air be directed against a pane of glass, the glass takes the vitreous electricity. A dry silk handkerchief, on being shaken in the air, is electrified resinously.

Although friction is the most common, it is not the only means of developing electricity. It is produced also by a change of temperature, as in the fusion of metals and other substances. Melted sulphur being poured into an insulated metallic vessel, is found, in cooling, to take the vitreous electricity, and the metal the resinous;

the phenomena are sometimes reversed, but the two kinds of electricity are always produced at the same time.

Several crystallized minerals of a vitreous nature have also the property of becoming electrical when heated to a certain degree. One extremity of the crystal takes the vitreous electricity, and the other the resinous, so that the parts where the two electricities prevail are separate; still they are simultaneously produced.

Finally, electricity is also developed by various chemical combinations, and indeed by the simple contact of all heterogeneous substances; but this branch of the science requires much more complicated and delicate instruments than any of which we have yet spoken; we shall therefore defer the consideration of it for the present.

Of the Laws which govern the apparent Attraction and Repulsion of electrified Bodies.

7. The phenomena of electrical attraction and repulsion being made known, the next thing to be done is to determine the laws according to which these forces are exerted at different distances. Here we have occasion to make use of the torsion balance, which has been successfully applied by Coulomb to the investigation of the laws of the variation of electrical and magnetic forces.

The essential parts of this instrument consist of a vertical wire, the upper end of which is attached to a movable index, while the lower carries a horizontal needle. When very small forces are to be measured, they are made to act upon the extremity of this needle, and their intensity is estimated by the angle through which they cause it to move from its point of rest; in other words, these forces are balanced by the force of torsion, which is always proportional to the angle of torsion.*

8. To apply this instrument to the measurement of electrical attraction and repulsion, we make the needle of gum lac, which is

* See note on the torsion balance.

a very good non-conductor, and attach to one of its extremities a
Fig. 5. small ball *b*, of elder pith. Then, having placed the index to the graduated circle *M* against zero of its divisions, we turn the whole cap, together with the index, till the ball *b* is opposite to zero of the divisions traced upon the sides of the instrument.*

This being done, we fix a second ball *a* at the extremity of a very small cylinder of gum lac, of such a length that being introduced vertically within the glass covering, this ball may reach the level of the other; and it is to be so placed that the ball shall answer to zero of the lateral divisions, which requires the first ball to be moved from this point, one way or the other, through an arc equal to the sum of the radii of the two balls; and the small torsion which results from this motion, is sufficient to keep them in contact.

Now it is manifest, that if we touch these balls for an instant, or only one of them, with a body already electrified and insulated, they will be electrified by communication, and both in the same manner; they must therefore mutually repel each other; but as the first only is movable, the needle which carries it will turn through a certain arc, and after oscillating backward and forward a little, it will come to a state of equilibrium at a point, the distance of which may be read off upon the graduated paper. Thus the degree of torsion of the wire will counterbalance the repulsive force of the two balls, and will serve to measure it.

This is in fact the course to be pursued; but as an extremely small force is sufficient to twist a fine wire through a very great angle, it is obvious that the balls will require only a very small charge of electricity. For this purpose, we simply touch them

* These divisions are made upon a piece of paper, which is afterwards pasted horizontally around the glass covering. If the covering is circular, the divisions will be in degrees. But when we wish to introduce bodies of a considerable magnitude, glass cylinders, as they are commonly blown, are too small, and we make use of four vertical panes, which, together form a parallelopiped. In this case, the strip of paper containing the graduations, requires to be divided into tangents, zero being at that point on each pane, where the needle is perpendicular to the pane.

with the head of a large pin, electrified by communication, the body of the pin being concealed in a stick of sealing-wax; the contact is effected by means of a small aperture in the glass covering made for this purpose, the stick of sealing wax serving as an insulating handle.

Proceeding in this way, Coulomb found in one of his experiments that after the electricity was communicated, the needle described an angle of 36°. He then twisted the suspending wire in a contrary direction, so as to bring the needle to the distance of 18° from the fixed ball, and in order to this he was obliged to turn the index 126°.

Finally, he twisted the wire so as to bring the needle to the angular distance of only 8½°, when the whole motion of the index was found to be 567°.

During this experiment, the balls did not sustain any sensible loss of electricity. For by previous trials on the same day, Coulomb ascertained that electrified balls, diverging 30° from each other, lost only one degree of their divergence in three minutes; and as he employed only two minutes in making the above experiment, we may safely neglect as insensible the diminution of electricity sustained by the balls, either on account of the contact of the air, or by loss along the supports. This was owing, as we shall see by and by, to the dryness of the air at the time of the experiment, and to the excellent choice of the insulating supports.

In order to obtain the results to be derived from this experiment, let us represent by *a b d* the circumference described by the movable ball *b*; let *c* be the centre of this circumference, and let us take the arc *a b* equal to 36°, the first distance to which the ball was repelled. It appears that in this case the repulsive force of the two balls, was counterbalanced by a torsion of 36°, exerted in the direction *a b*; for by the arrangement made at the commencement of the experiment, the torsion is nothing when the needle is directed toward the point *a*. Fig. 6.

In the second case, the wire was twisted 126° in the direction *b a*. If the needle were free, this torsion would carry it to *d′*, 126° beyond the point *a*; but, on the contrary, the repulsive force retains it at *b′* 18° this side of *a*. Therefore at this point the re-

pulsive force of the two balls would hold in equilibrium a torsion of 126° + 18° or 144°.

Finally, in the third case the torsion indicated by the graduated circle, was 567°, always in the direction *b a*; but instead of going 567° beyond the point *a*, the needle stood at 8½° on this side of the point; thus the repulsive force which kept it at that distance was equivalent to a torsion of

$$567° + 8\tfrac{1}{2}° \text{ or } 575\tfrac{1}{2}°.$$

Accordingly we have in the following table the relative torsions and distances.

Angular distance of the two balls.	Measure of the repulsive force by the torsion.
36°	36°
18°	144°
8½°	575½°

A remarkable law is hence manifest. The angular distances, contained in the first column, are nearly as the numbers 1, ½, ¼, while the corresponding torsions, which measure the effect of the repulsive forces upon the needle, are as the numbers 1, 4, 16, that is, inversely proportional to the squares of the preceding. These ratios, therefore, make it evident that the electrical forces, like the attractions of the heavenly bodies, are in the inverse ratio of the squares of the distances.

Strictly speaking, the distance of the two balls is the chord of the arc by which they are separated, and not the arc itself. Moreover, the repulsive force which they exert upon each other acts obliquely, and consequently is not wholly employed in producing the divergence. But this obliquity is very small in our experiments, on account of the small extent of the arcs; and for the same reason, there is very little difference between the arcs and their chords. It will hence be perceived, that our conclusions are fairly made out. But we may put the subject beyond all

doubt, by performing the calculation in a rigorous manner. We thus find, that where the arcs of divergence do not exceed 36°, the ratios deduced from the arcs, and those obtained from the rectilineal distances, do not differ by any sensible quantities. Confining ourselves, therefore, within these limits, we may apply the law of the squares of the distances to the arcs themselves, and thus very much simplify the calculations.

9. The wire employed by Coulomb in his experiments was of silver, and on account of its fineness, its sensibility as to torsion was very great. Other instruments still more sensible were invented by the same philosopher for the purpose of indicating the minutest quantity of electricity. These instruments, which we shall call *electroscopes*, are true electric balances, in which a single fibre of silk, as it comes from the silk-worm, takes the place of the metallic wire, while the needle is a small thread of gum lac, about an inch in length, terminated at one of its extremities by a very small disc of tinsel.* In one of these instruments used by Coulomb, the weight of the needle and the tinsel together did not exceed ½ of a grain. A fibre of silk of four inches in length, has such a flexibility, that with a lever an inch long, it requires a force equal only to the sixty-thousandth part of a grain to twist it 360°. To communicate the electricity to the disc, we pass through a stick of sealing wax, a copper wire, terminated at one end by a small ball of elder pith gilt, and at the other by a metallic ball, or by a hook the point of which returns into the wax. This stick thus armed is introduced into the glass covering, the hook being outward, and it is so fixed that the centre of the gilt ball, being seen in the direction of the suspending wire, answers to zero on the sides of the covering. Fig. 7.

* These threads are easily formed, by warming in the flame of a candle the middle of a small stick of gum lac, and holding it at the same time by its two extremities. When the resin begins to melt, we pull the two ends rapidly asunder, and the melted matter is commonly drawn out into a very fine thread, which adheres to the two solid ends. In the same way we draw out threads of sealing wax and even of glass; but for the latter substance, unless we employ a tube already very fine, the heat of a candle is not sufficient, and we are obliged to use a blow-pipe.

When the needle is at rest, we turn gently the index to the graduated circle till the tinsel comes in contact with the gilt ball; the instrument is then ready for use. If we communicate electricity to the hook, it is transmitted to the ball and to the tinsel disc, which is immediately repelled. The sensibility of these electroscopes is such, that if after having electrified by friction a stick of sealing wax, it is presented to the exterior hook, even at the distance, for example, of three feet, the needle is immediately repelled more than 90°. We shall see hereafter how electricity may be thus developed at a distance without any contact. At present we give this result only as a proof of the extreme sensibility of the instrument. By means of this electroscope, it would be easy to repeat all the experiments mentioned in the preceding chapter, on the nature of the electricity excited in different bodies by their mutual friction.

10. After having determined the laws of electric repulsion, we naturally direct our attention to those of attraction exerted between bodies charged with different electricities; and here also we follow the example of Coulomb. But in this case the balls must not touch each other in their first position before being electrified; on the contrary, they must be separated, and the torsion must prevent them from uniting. For this purpose, we begin with taking away the
Fig. 8. fixed ball *a*; and by means of an insulated pin-head, we give to the movable ball an electricity of a certain kind, for example, the resinous. This being done, we turn the index through a certain known angle *c*; the wire being free will follow this motion, and after some oscillations, the extremity of the needle will come to a state of rest before a certain point *b* of the lateral divisions, which will be *c* degrees distant from its first position. This operation will therefore have transferred the zero of torsion through the known angle *c* in the direction *a b*.

We now replace the fixed ball *a* and give it a different electricity from the former, that is, the vitreous. The two balls being attracted toward each other, the needle will move toward the fixed ball *a*, and *if an equilibrium be possible*, it will stop at some point *b'*. We note this point, and then turn the graduated circle backward and forward through known angles, for the purpose of varying

the torsion, and we note in each case the points where the needle becomes stationary. Comparing these torsions and distances, as in the experiment on the variation of repulsive forces, we shall find that the same law obtains in both. We conclude, therefore, that the attractive forces exerted between different electricities, like those of repulsion in the case of electricities of the same kind, are inversely as the squares of the distances.

In the above experiment, a precaution is to be observed, without which we should not succeed. When the attractive force of the two balls causes them to approach each other, the intensity of the attraction increases as the distance becomes less, and if no other cause came into operation, they would come in contact. But the torsion is opposed to their approach, and the resistance increases as the needle departs from the point *b* towards the other ball. Now within a certain distance this resistance does not increase rapidly enough to overcome the increase of the force of attraction, so that an equilibrium being impossible, the balls having reached this point, approach more and more, and finally unite. A very simple calculation would make this evident, and determine the limits of departure to be observed.

It even happens, sometimes, that they still unite under the circumstances in which, according to the calculation, an equilibrium is possible. This takes place because the suspending wire admits of an oscillation in the needle, for some time, about the point of equilibrium where it must finally stop. If the extent of these oscillations be such as to carry the movable ball sufficiently near to the fixed ball for the attraction to increase more rapidly than the force of torsion, this torsion will not be sufficient to bring back the needle, and the balls will come in contact.

11. Coulomb has also determined the law of electric attraction by another method, which I shall describe here, because it serves to verify the preceding, and also because it will be of use when we come to treat of magnetism. It consists in suspending horizontally, by a single fibre of silk, a needle of gum lac, the extremity of which carries a disc of tinsel, which is to be electrified. Before this needle, at some distance, we place a globe charged with a different electricity, which attracts it and causes it to oscillate in virtue of its action. We then determine by calculation the attractive force at different distances

of the electrified globe, from the number of oscillations of the needle which take place in a given time, just as we determine the force of terrestrial gravity from the number of oscillations of the common Mech. 348. pendulum. The results thus obtained confirm the law of the inverse duplicate ratio of the distance, before discovered by means of the torsion balance.

12. The same method would serve also to determine the law of repulsive forces; for by communicating to the globe and to the disc similar electricities, the disc will be repelled, the direction of the needle will be inverted, and it will oscillate in virtue of this repulsion in a direction diametrically opposite to the former; but with the exception of this turning, which will affect the distance of the disc from the globe, the observations and the calculations will be the same as in the preceding case.

By means of the results which we have obtained, we can calculate, for all possible distances, the force of attraction or repulsion of two electrified balls, when we have determined this force for a single known distance.

But this gives us only the measure of the total effect; we do not know what proportion each ball contributes. Still, unless they are perfectly equal and equally electrified, it is manifest that they must contribute unequally. It is proposed, therefore, to discover this proportion; which is readily done, if we could give to one of the balls, or take from it, a portion of electricity having a known ratio to that which it had before. For, by measuring the new torsion which produces an equilibrium in this new state, and comparing it with that which took place before at the same distance, we should discover what influence the proper electricity of each ball has upon the total effect. Now it is very easy to take from each ball half its electricity. To this end, we have only to touch it for an instant with another ball of the same substance, of the same diameter, and equally insulated; for it is manifest that the two balls being perfectly similar, the electricity will be equally divided between them, so that after the contact, the proper action of the ball touched will be less by one half. Now by proceeding in this way, we find that the total force of attraction or repulsion, which was at first exerted between this ball and the fixed ball of the balance, is, after the contact, reduced exactly one half.

This method of reduction is not confined to balls, but extends to circles, and probably to all bodies whose figure or distance asunder is such, as to admit of their being considered as points. Coulomb substituted instead of the fixed ball of the balance, an iron circle $\frac{5}{8}$ of an inch in diameter, leaving always a pith ball at the extremity of the needle. He electrified these two bodies simultaneously by means of the head of a pin, and the repulsive force separated the needle from the circle; when it was brought back and placed at a distance of 30°, the index pointed to 110°; the repulsive force, therefore, was 140°. He then touched the little iron circle by another of the same substance and same diameter; the needle immediately approached the circle, and to bring it back to the distance of 30°, it was found necessary to untwist the wire till the index stood at 40°; therefore the repulsive force was reduced to 40° + 30° or 70°, the half of 140°, the measure of its former intensity.

13. By these experiments, moreover, we are made acquainted with a remarkable fact, namely, that the distribution takes place in exactly the same proportion, whatever be the substance of the conducting bodies placed in contact, provided their forms and dimensions are the same. Coulomb touched the fixed pith ball with a ball of the same size of copper and of several other substances; he touched the iron circle also with a circle of paper of the same diameter; and the distribution was always into equal parts.

14. These experiments lead to two important conclusions. The first is, that the total force of attraction or repulsion, varying for each distance in the same ratio as the quantities of electricity belonging to the two bodies, it follows necessarily that the expression for the force in question is proportional to the product of these two quantities. Then each ball or each circle contributes to the entire force which attracts or separates them, according to the value of the factor which it introduces into this product. In future we shall call this factor the *electrical reaction* of the ball or circle of which it measures the action, and we shall extend by analogy the same denomination to all bodies of whatever form, when we observe their electrical action at so great a distance that they may be considered as simple points.

15. The second conclusion is, that, since the distribution of electricity between conducting bodies of the same size and figure, takes place always in equal proportions, whatever be the nature of the substance, it follows that these bodies do not act upon electricity by a chemical affinity depending on the nature and arrangement of their material particles, but are, with respect to it, merely vessels or receptacles in which it distributes itself mechanically according to its own proper laws.

Of the Laws according to which Electricity is dissipated by the Contact of the Air, and along the Supports which retain it but imperfectly.

16. The general law of electric attraction and repulsion will be understood from what precedes; but to verify with exactness the consequences to be deduced from it, and to follow out the electric principle into its most minute effects, we must assure ourselves of its uniform intensity, or at least determine the laws according to which this intensity diminishes by contact with the air and by the imperfection of the insulating supports. Such is the object of this section, for the substance of which we are still indebted to the labors of Coulomb.

17. When an electrified conducting body rests on insulating supports, its electricity diminishes more or less rapidly, and finally disappears. Many causes conspire to produce this effect. In the first place, there probably does not exist in nature a perfectly insulating substance; for we know no one which does not transmit, at least along its surface, a strong electricity; glass, sealing wax, even gum lac in this way transmit it sensibly, although with difficulty. Of this we may satisfy ourselves by forming cylinders of these substances; and holding them successively for some time in contact, at one extremity, with the prime conductor of an electrical machine. For, upon taking away the cylinder and presenting this same extremity to the needle of the electroscope, we shall see that it is impregnated with the electricity of the conductor; and even on cutting off the end of the cylinder, we shall still find that

the electricity is also propagated over the rest of the surface to a certain distance, with decreasing intensity.

All the supports employed to insulate an electrified body, must draw off more or less of the electricity; and if they are short enough to be thus electrified throughout their whole length, they will cause a gradual but continual waste, so that from this circumstance alone the electrical reaction of the insulated body must become weaker and weaker.

18. Secondly, electrified bodies are always surrounded and in contact at every point of their surfaces, with the atmosphere which transmits the electricity with greater facility, according to the quantity of aqueous vapor which it contains; and perhaps, according to modifications arising from heat and other circumstances, in the very properties of its chemical elements, so that we may generally regard it as composed of an infinity of more or less perfectly conducting atoms. Accordingly, each particle of air which touches an electrified body must take a part of its electricity. But after it is impregnated in the proportion which belongs to its magnitude and conducting power, it is immediately repelled, and its place is taken by another, which is also electrified and driven away in its turn; and thus by the effect merely of these successive contacts, continually renewed, the electricity of bodies must diminish, according to a progression depending on the conducting power of the air.

Finally, the aqueous vapour suspended in the atmosphere contributes to this dissipation in another way; for it attaches itself to the supports in greater or less quantity, according as it is more or less abundant, and according as the matter of the supports has greater or less affinity for water. Such of these particles as are nearest to the electrified body, receive the electricity from it immediately; and if the force with which they are then repelled by it is less than their adhesion to the support, they must transmit this electricity in part to the neighbouring particles, and they, in the same way, to the next; so that all these particles being good conductors, form, as it were, a chain upon which the electricity must go on decreasing from the conducting body, but which, nevertheless, will finally conduct it to the ground, if the support is not long enough to prevent it. If the particles which form this chain are nearer to each other than those in the air itself, which is often the

case, the electricity will be dissipated more rapidly along the support than by the contact of the air; and this frequently happens, as we shall presently see.

19. Whatever difficulty there may seem to be in guarding against the last cause of dissipation, it will be seen to be indispensably necessary to do it in order to be able to determine the loss of electricity occasioned by the contact of the air simply, and for the purpose also of making allowance for this same cause of waste, in experiments where it is blended with the loss occasioned by the supports. The only means of effecting so important an object, is to choose for supports the substances which insulate best, and to make them so small as to admit, in contact with their surfaces, but few particles of water or other conducting matter in comparison with the surrounding atmosphere; for in this case the support will insulate, to say the least, as well as the air, and the extent of its contact with the electrified body being very small we may neglect its effect entirely.

By several experiments conducted upon this principle, Coulomb found, that when the intensity of the electricity was not very great, a small cylinder of sealing wax or of gum lac, $\frac{1}{24}$ of an inch in diameter, and $1\frac{1}{2}$ inch in length, was almost always sufficient to insulate perfectly a pith ball of $\frac{1}{2}$ of an inch in diameter. For the electricity was not dissipated any faster when the ball was supported by several of these cylinders, than when it was supported by one only, although the facility for dispersion was increased with the number of points of contact. He ascertained also that when the air was dry, a very fine thread of silk drawn through boiling sealing wax, and thus forming a little cylinder of not more than $\frac{1}{48}$ of an inch in diameter, answered the same purpose, provided its length was 5 or 6 inches. A thread of glass drawn out in an enameller's lamp to 5 or 6 inches in length, will not insulate the ball except in very dry weather, and when it is feebly charged with electricity; the same may be said with respect to a hair or a silk thread, at least if they are not covered with sealing wax, or, which is better, with pure gum lac.

20. After making these preliminary experiments, Coulomb soldered the fixed ball of the balance to the end of a thread of pure gum lac $1\frac{1}{2}$ inch in length, which was terminated with a very fine

thread of silk covered with sealing-wax, so that this ball might be considered as perfectly insulated. The movable ball was no less so, since the needle which carried it was also a very fine cylinder of gum lac. Coulomb first made these two balls of equal diameter, and he employed a balance of such sensibility, that the torsion of an entire circumference, answered to a force at the extremity of the needle of $\frac{1}{340}$ of a grain. The zero of torsion of the wire being brought to the centre of the fixed ball and the two balls being in contact, they were touched, as in the former experiment, with the electrified head of a pin; the movable ball was repelled, and, after several oscillations, fixed itself at a certain distance from its point of departure, for instance, at 40°.

The suspending wire was then twisted so as to bring it back to a less distance, as 20°, for example. To do this, it was necessary to turn the index of the graduated circle 140°. Thus the torsion, equal to the repulsion of the two balls, was 140° + 20° or 160°.

The moment when the movable ball was stopped at this distance, was observed with a seconds-watch, and found to be 50 minutes after 6.

As the electricity is dissipated by the contact of the air, the repulsive force of the balls gradually diminishes; and after some minutes they become nearer to each other than 20°. To bring them again to this distance, we untwist the wire by a known quantity, for example, 30°. Its force of torsion being diminished by this quantity, the movable ball is driven further off than 20°.

We wait till the loss of electricity brings it back to this distance and observe the time. This was found to take place at 53 minutes after 6, and consequently, 3 minutes after the first observation; the force of torsion then equal to the repulsion of the two balls, becomes

$$140° - 30° + 20° \text{ or } 130°.$$

The loss of repulsive force between the two experiments, was therefore equal to 160° — 130° or 30°, that is, to the quantity by which the wire was untwisted to bring the balls to the same distance. This effect was produced in 3 minutes; and as in small intervals we find it is proportional to the times, it follows, that the loss

is 10° a minute. Moreover the mean repulsive force between the two experiments, was $\frac{160° + 130°}{2}$ or 145°. Comparing this with the observed diminution, we see that the electrical force of the two balls diminished on this day by $\frac{10}{145}$ or $\frac{1}{14\frac{1}{2}}$ a minute, on account of the contact of the air only.

By experiments of this kind, Coulomb constantly found that on the same day, and with the same state of air, the loss of electricity for a short time was proportional to its intensity, and that thus the ratio of these two elements is invariable. But this ratio changes with the state of the hygrometer, and consequently with the quantity of aqueous vapour suspended in the air.

21. A greater number of experiments on this subject would serve to discover the ratio between the quantity of aqueous vapour, and the greater or less rapidity with which the dispersion of electricity takes place. We might thus determine also whether this vapour is the sole cause of the phenomenon, or whether the pressure and temperature of the particles of the air itself are not also concerned. If we were able to estimate the influence of these different causes, we should perhaps find the electrical balance to be the most exact and sensible of all hygrometers. We might at least, from the simple indications of meteorological instruments, assign the proportional loss of electricity sustained. For want of these data we are obliged to determine this proportion directly by experiment for each particular time, when we have occasion for exact experiments on the intensity of electrical forces.

22. It is very fortunate for us in our experiments, that the law of decrease happens to be so simple; since, for the same state of the air, it is proportional to the repulsive force, we have occasion only for a single experiment each time, in order to apply the necessary correction to any number of cases. Moreover, the law which we have discovered, enables us, when the intensity of an electrical force and its rate of decrease are once determined, to calculate it for any other given moment. By examining the results thus obtained, we learn that the same law of decrease is applicable to cases where the two bodies acting upon each other, are of unequal magnitudes, and charged with unequal quantities of electricity. Indeed, what-

ever be the magnitude of the fixed ball compared with the movable one, and whatever be the quantity of electricity at first given to them, whether they are electrified simultaneously, or one after the other, and in whatever proportion, the momentary decrease of their whole repulsive force, measured at the same distance, is always in the same proportion to its intensity; and thus our experiments are all equally suited to the purpose of finding this common ratio. Moreover, this ratio is still the same when we employ balls of different substances. The nature of the substance has absolutely no influence on the loss of electricity occasioned by the contact of the air, at least with respect to the portion which acts at a distance by attraction and repulsion; and this confirms the observation which we have before made, that material bodies do not seem to retain the electric principle by any proper affinity, but by the effect simply of the resistance which is opposed to it by the surrounding air. For example, in weather when the electricity was decreasing at the rate of $\frac{1}{82}$ a minute for each of the pith balls of the balance, Coulomb found that it decreased also $\frac{1}{82}$ when he substituted for one of these balls a ball of copper; and, which will appear still more extraordinary, the decrease was also $\frac{1}{82}$ for a ball of sealing wax, which had been charged with electricity, by bringing it in contact with a body strongly electrified; and thus the surface of such a body opposes no difficulty, to the transmission of the electric principle, and has no influence in retaining the portion of this principle, which manifests itself by its reaction, when once it becomes free.

23. We have as yet considered only bodies of a globular shape; but whatever may be the figure of the electrified body, whatever its magnitude and the distribution of its repulsive force, if the air is very dry and the electricity communicated not very intense, the momentary decrease of the repulsive force is always the same, and preserves always the same ratio to its intensity. This was demonstrated by Coulomb with a globe of a foot in diameter, and with cylinders of all diameters, and all lengths. He substituted for the balls of his balance, circles of paper or metal; he also, in one instance, armed one of them with a copper wire $\frac{5}{6}$ of an inch in length, and $\frac{1}{60}$ in diameter; and he found that, at the time of his experiments, the repulsive force of all these bodies, although so different

in form, decreased by the same quantity, namely, $\frac{1}{100}$ in a minute. But it is necessary to remark, that this equality of decrease for bodies of different forms take place only when their electricity is already considerably reduced, and reduced so much the more, according as the air is more moist. For all angular bodies, when possessed of a strong electricity, lose at first this excess by a much more rapid decrease, as we shall have occasion to show hereafter, when we come to speak of the electricity of points. This phenomenon may be rendered evident to the senses, without the aid of the balance, by connecting the prime conductor of an electrical machine with a metallic bar, having sharp angles or points. For, upon putting the machine in motion, the experiment being performed in the dark, the electricity communicated to this bar, will produce, as it flies off from the points, beautiful tufts of light. I do not mean to say that this fire is itself the electricity, for herein is involved a question to be examined hereafter; but as light always attends the rapid escape of electricity, it is at least a sign and indication of this escape. It would be well worth our attention to inquire whether, the state of the air being the same, the two kinds of electricity are dissipated at the same rate. I have made the examination, and find that this is in fact the case.

24. The law of the gradual dispersion of electricity, produced by the mere contact of the air, being thus known, Coulomb proceeded, according to the same method, to determine that occasioned by the imperfect insulation of the supports.

The course which first suggests itself, is to choose such substances for supports, that the loss arising from this cause shall be very great, compared with that depending upon the contact of the air. But this very rapid decrease would be attended with a serious inconvenience. For every time we touch the balance, either to give the balls their first electricity, or to change the torsion by means of the graduated circle, the needle does not return to a quiet position till after several oscillations. It is therefore necessary that the insulation should be pretty perfect, that the electricity may not sustain in this interval very great variations of intensity, and that we may be able to make several experiments of this kind successively, without giving to the balls a new charge. Accordingly, Coulomb instead of suspending the fixed ball of the balance to a cylinder of

gum lac, attached it to a single fibre of silk, as it comes from the silk worm, of about fifteen inches in length. The movable ball at the end of the needle was always insulated as perfectly as possible, and made equal in magnitude to the other. Coulomb measured, as before, the repulsive force of the two balls at different times, and hence calculated the decrease of the electricity. He found this decrease to be much more rapid than that produced by the air alone, when the intensity of the repulsive force was considerable, but that it became gradually less rapid as the intensity diminished; and thus at a certain point, the ball, supported by the silk fibre, lost precisely as much as when it was insulated in the most perfect manner; and this *limit* being once attained, the same equality continued through the lowest degrees of intensity. We hence learn, that at this point the thread begins to insulate perfectly.

In these experiments, the movable ball can lose its electricity only by the contact of the air. We may therefore calculate for any instant, the state of its electrical action from the law of decrease above established; and as the whole repulsive force, obtained by observation, for this instant, makes known the amount of the reciprocal electrical action of the two balls, we can thence deduce, for the same instant, the electric action of the fixed ball. By this calculation, therefore, the effect of imperfect insulation is determined. Applying it to the experiments we have mentioned, Coulomb was able to fix the degree of electrical action at which each of the supports used by him began to insulate perfectly; and he found that the intensity of this action was proportional to the square root of their respective lengths; in other words, that for the same state of the air, a quadruple length of support insulates perfectly a double quantity of electricity; it being well understood that this proportion is restricted to supports of a cylindrical form, which differ only in respect to length. When the substance or its figure is changed, it is necessary to deduce the ratio from the formula itself. Calculating in this way, from experiment, the intensity of the electrical action, at which perfect insulation begins, in the case of threads of gum lac and of silk of the same length and diameter, we find that it is ten times greater for the first substance than for the second. By similar calculations we may compare

together the conducting power of all substances which transmit electricity imperfectly.

In order thus to compare one substance with another, it is by no means necessary that the balls of the balance should be observed at the same distance in the two series of experiments; it is enough that this distance be constant in each series, and that we substitute its value each time in the formula. It is equally immaterial what degree of electricity we give to the balls. But it is always necessary that they should be equal and simultaneously electrified; it is also necessary that they, as well as the torsion wire, should be the same in all the experiments; otherwise the ratio of the torsions to the repulsive forces would not be the same in the different series, which would render the comparison of them more difficult and less direct. These are the only indispensable precautions to be observed.

Of Electricity in a State of Equilibrium in insulated Conducting Bodies.

25. Knowing how to reduce the electrical action of bodies to a constant state, notwithstanding the continual loss which takes place by the contact of the air, and along the supports, we are prepared to inquire into the mode in which electricity distributes itself among the different parts of the same body, both in its interior and at the surface.

Now, from what we have already learned upon this subject, it would seem very probable that the electricity is confined entirely to the surface of conducting bodies, and that their interior particles have no effect in retaining it; otherwise, it is not easy to perceive how the mere circumstance of equality of surface in the case of two bodies in contact, should produce between them an equal division of electricity, whatever be the substance of the bodies themselves, or how this equality should take place when one of the bodies is solid and compact, and the other hollow and presenting scarcely any thing but a simple surface; whereas all these things become simple and intelligible, on the supposition that the electricity, in a state of equilibrium, is diffused only over the surface of bodies, without penetrating into the interior.

26. This property, suggested to us by analogy, is of sufficient importance to be made the subject of direct investigation.

It may be rendered evident, in the first place, by the following experiment. Take a conducting body *S* of a spheroidal figure; Fig. 9. form in like manner, of a conducting substance, two very thin caps *E*, *E*, of gilt paper, for instance, and give them such a shape, that being joined, they will exactly cover the body *S*, attaching to them tubes of gum lac *EM*, *EM*, by which they may be removed and replaced, without being deprived of their electricity. This done, put the body *S* upon an insulating support, or suspend it by a very fine silk thread covered with gum lac, and give it any portion whatever of electricity. Then, after touching the two caps to make it certain that they are not electrified, place them upon the spheroid *S*, holding them by the extremities of their insulating handles; after a moment's contact, withdraw them, and present them to an electrical pendulum. We shall find that they have taken off the electricity of the spheroid, and taken it entirely.

27. We may also verify this property in another and more general way; for the body, submitted to trial, may have any form whatever, and the experiment be made without taking from it any of its electricity. We have only to pierce the surface of this body with one or more small cylindrical holes $\frac{1}{5}$ of an inch in diameter and of any depth; we next draw out a thread of gum lac of several inches in length, to the end of which we attach a small circle of gilt paper, like that of the needle of the electroscope, and having a diameter of $\frac{1}{3}$ or $\frac{1}{4}$ of the size of the holes. This being done, we insulate the body *S*, and electrify it strongly by sparks from the prime conductor of an electrical machine, or in any other way; then holding the thread of gum lac by its free extremity, we carefully introduce the gilt circle attached to it into one of the openings of the body *S*, taking care not to touch the edges of the opening. Upon withdrawing the circle, it will be found not to possess the minutest portion of electricity. But if, after having repeated this experiment with the same result, we touch the circle for an instant to the exterior surface of the body *S*, or only to the edge of one of the cavities, it will be seen to exert a lively action upon the needle of the electroscope. We infer, therefore, that the electricity of the body *S* resides wholly on its surface, and not at all in the interior.

Not only is there none in the interior, but it is impossible to fix any there; for if we charge directly the circle of gilded paper, by taking the electricity from another body or from the exterior surface of the body *S*, and then introduce it into the cavity of this body, all the electricity which it had acquired abandons it, and passes into the body enveloping *S*, where it immediately gains the exterior surface; and the little plane being withdrawn from the cavity where it was introduced, is found to be discharged.

This result applies generally to all bodies of whatever figure; but on repeating the experiment, we sometimes find that the gilt circle, on being withdrawn from one of the cavities, shows some feeble signs of an electricity of a contrary nature to that of the body *S*, and which does not disappear even when we touch the circle in order to discharge it. The circumstance of this electricity being thus permanent, proves that it does not belong to the gilt circle itself, but is communicated to it by the gum lac, which restores it as fast as it is taken off; and accordingly we can derive from it no evidence of the existence of electricity in the interior of the body *S*. Now how could the thread of gum lac, which carries the circle, without touching the edges of the aperture and by proximity alone, thus acquire an electricity contrary to that of the body *S*? This phenomenon will be explained soon, when we come to treat of the development of electricity at a distance, or of what is called induced electricity. For the present I shall merely observe, that this effect, which is purely accidental, is almost always insensible when the gum lac is pure, the air dry, and the cylinder suffered to remain in the cavity only for a short time.

We may rest assured, therefore, that the electric principle, whatever it may be, resides on the surface of conducting bodies, and not in their interior. We know, moreover, by further experiments, that the air retains it upon the surface, and is the only obstacle which prevents its escape from the body. Hence, combining these two facts, it will be seen that the electric principle always distributes itself over conducting bodies in a very thin stratum, whose exterior surface, being contiguous to the air, and confined by the pressure of this fluid, is the same as that of the electrified body, while the inner surface, almost coincident with the other, since the stratum is very thin, must be determined according to other laws, to be deduced from observation or nice calculation.

28. For example, when the electrified body is a sphere, the circumstance of symmetry alone requires that the inner surface should also be spherical and concentric with the outer; for it must, like the body itself, be symmetrical in every direction about the centre. When we accumulate successively upon a sphere greater and greater quantities of electricity, we may suppose, either that the newly added quantities dispose themselves spherically under the first, and augment the thickness of the stratum, or that the thickness remaining the same, the density of the electricity is augmented at each point. It is of no importance, in practice, which way we consider it; for the thickness of the stratum being always very small, all the electrical particles collected under each infinitely little superficial element, must act by attraction or repulsion upon external bodies just as if they were all concentrated in a single point, and consequently as if they were infinitely condensed. Thus their action will always be proportional to their number, in whatever way they are regarded. But, considering the subject physically, the notion of a thickness essentially limited does not seem natural; for there is no obstacle in the interior of a conducting body, to prevent the electricity from spreading in that direction; if it does not so spread itself, it must be on account of the laws of its equilibrium; and for this reason it becomes extremely probable that for each given quantity of electricity, the thickness of the electrical stratum depends, in like manner, upon these laws.

29. The above method of trying the electricity of a conducting body, by touching it with a circle of gilt paper, insulated at the end of a thread of gum lac, is applicable to a variety of cases. It will serve to show, not only the existence and the nature of this electricity, but also the absolute quantity which may be collected upon each point of the surface. For this purpose, instead of presenting the little plane to the electroscope, as in the preceding experiment, we substitute it for the fixed ball of the balance and observe its action upon the movable ball or circle, previously charged with electricity of the same kind. The small magnitude of these bodies, permitting us to consider them as points, it is manifest that the electrical action of the small plane will be proportional to the quantity of electricity with which it is covered; and if we always introduce it into the balance without any loss being sustained by the movable

ball or circle, the torsions necessary to bring them successively to the same distance will give the ratios of the different charges. Now, since a very small plane applied to a body is confounded with an element of its surface; we must presume that these charges will also be proportional to the charges of the points where the circle is applied. And we may thus hope to determine how the quantity of electricity, or which amounts to the same thing, how the thickness of the electrical stratum varies upon different points of a body on which the electricity is not uniformly distributed.

Take, for example, a conducting body of any figure whatever, and place it upon an insulator, and, after having given it a certain portion of electricity, touch it with the small plane in a point a, capable of being exactly determined; place this plane in the balance, previously charged with electricity of the same kind, and observe the torsion necessary to counteract the repulsion at a given distance D; let this torsion be represented by A.

Then withdraw the little plane, and touch the conducting body in another point a', different from the former, but capable in like manner of being determined, and apply it to the balance, ascertaining the torsion necessary to bring the needle to the point D, as in the first experiment. Let this torsion be $n\,A$, its ratio to the first being expressed by n. If, after an interval of some minutes, we repeat these experiments, placing the little plane upon the same points a, a', we shall not find the same absolute torsions as before, because the insulated body will have lost a part of its electricity by contact with the air; but the ratio of these torsions will remain the same. If the first becomes A', the second will be $n\,A'$. In order that the comparison may be perfectly exact, there should be the same interval between the successive contacts of a and a' as in the first experiment.

We shall arrive at similar results, however often we may choose to repeat the experiment, and the ratio of the torsions will continue the same as long as there remains a sensible quantity of electricity upon the insulated body. Moreover, if we have noticed the times at which the successive experiments have been made, we shall see that the absolute decrease of the torsions is exactly such as ought to result from the simple contact of the air; in other words, the mutual repulsion of the small plane and the movable circle, at any

moment, is exactly the same as if we had left the plane in the balance with the charge of electricity which it had taken from the point *a* or *a'*, in its first contact. Consequently, the absolute quantity of electricity received at each contact, is proportional to the actual and total amount of electricity in the body.

This proportion may also be made evident by the following experiment.

30. Let the insulated body be a cylinder or a rectangular parallelopiped, the length being much greater than the breadth; upon electrifying it and touching it with the little plane, first in the middle, and then at one of its extremities, we shall find the electrical action in these two cases to be very different. If we now bring to the electrified body, another of exactly the same form and dimensions, also insulated, and present it to the first symmetrically, that is, in such a manner that the similar sides shall come in contact, each throughout its whole extent, the electricity will of course be divided equally between the two bodies; then, after separating them, if we repeat the experiment with the small plane, touching always the same points as before, we shall find that its electrical action is reduced, for each point, to exactly one half of what it was on the first trial.

We see, therefore, from these experiments, that the absolute quantities of electricity, successively taken off by the *trial plane* from the same point of the surface of a conducting body, are proportional to the whole amount of electricity spread over the surface of this body at the instant of contact; and, whatever may be this amount, that the quantities taken at the same instant from different points of the surface, preserve always the same invariable ratios among themselves. Hence we draw two conclusions; the first is, that in every conducting body, the accumulation of a double, a triple, &c., quantity of electricity gives to each point of the surface, a double, triple, and generally, a proportional quantity; the second is, that the trial plane, considered as infinitely small in relation to the whole surface of the conducting body, takes always at each point of the surface a quantity of electricity proportional to that of the point touched.

Proceeding in this way, each contact of the plane diminishes somewhat the absolute quantity of electricity of the body which it

touches, and consequently we ought, strictly speaking, to take account of this diminution, if we would bring our successive trials into exact comparison ; but this is rendered unnecessary by making the plane so small, that the quantity of electricity taken off by it, shall be inconsiderable in comparison with that of the whole surface of the body. If, in addition to this precaution, we would reduce the error still more, we have only to carry back the plane to the surface of the body without discharging it. Care should be taken also to support the little planes by threads of very pure gum lac, having the greatest insulating power.

31. As these experiments always require to be several times repeated, it is necessary, in comparing them with each other, to take notice of the loss of electricity occasioned by the contact of the air. This may be done according to the laws of decrease above given ; but we may dispense with this correction, also, by combining the experiments in such a manner, that they shall rectify each other. For this purpose, if it is proposed to compare the electrical action of two points *a* and *b*, we first touch *a* with the little plane, and observe the action which results. We then touch *b*, and observe the corresponding action. If there be a certain interval between the first and second observations, as three minutes, for example, we should touch *a* again three minutes after the second observation, and take the arithmetical mean between the two actions. We should thus have the same result as if the two contacts of *a* and *b* had been made at the same moment. This method of correction is to be preferred to any other. It even corrects the effects of loss along the supports, provided it is small, as it always is when they are well chosen and well prepared.

32. To give an example of the method of alternate contacts, I shall select the following experiment, which I find among the manuscript minutes of Coulomb.

He proposed to discover how electricity distributes itself upon a thin insulated plate. For this purpose, he insulated a plate of steel 11 inches in length, 1 inch in breadth, and $\frac{1}{24}$ of an inch in thickness. In order to touch it through its whole breadth, he made a trial plane an inch in length and $\frac{1}{4}$ of an inch in breadth. He first Fig. 10. applied this plane to the centre *C* of the plate, and afterwards at an inch from the extremity, and he obtained the following results ;

	Observed torsions.	Mean torsions at the centre.	Mean torsions at 1 inch from the end.	Ratio of mean torsions.
Contact at the centre.	370°			
At 1 in. from the end.	440	360	440	1,22
At the centre.	350	350	417,5	1,20
At 1 in. from the end.	395	335	395	1,18
At the centre.	320		Mean....	1,20

That is, upon equal spaces, taken throughout the breadth of the plate at the centre, and at an inch from the extremities, the quantities of electricity are to each other as 1 to 1,2, and therefore nearly equal.

Coulomb repeated the experiment, placing the trial plane exactly at the extremity, but resting wholly upon the surface, and he obtained the following results;

	Observed torsions.	Mean torsions at the centre.	Mean torsions at the end.	Ratio of the mean torsions.
Contact at the end.	400°			
At the centre.	195	195	395	2,02
At the end.	390	190	390	2,05
At the centre.	185	185	370	2,00
At the end.	350			
			Mean....	2,02

In this case the ratio of the quantities of electricity is much greater than in the preceding. Thus we see that while they are nearly constant from the centre to within one inch of each extremity, beyond this the electricity increases very rapidly.

Coulomb made a third experiment, placing the trial plane across the end of the plate at *D* so as to come in contact with both surfaces at once; he then obtained the following results;

	Observed torsions.	Mean torsions at the centre.	Mean torsions at the edge.	Ratio of the mean torsions.
Contact at the centre.	305°			
At the edge.	1175	295	1175	3,98
At the centre.	285	285	1156	4,05
At the edge.	1137			
			Mean....	4,01

Thus the trial plane being placed across the end of the plate, receives just double the electricity which it acquired at this extremity when it touched but one surface.

The experiment being repeated with a plate 22 inches long, that is, of twice the length of the preceding, and otherwise of the same dimensions, gave exactly the same ratios between the intensities at the centre and at the extremities.

33. Hence Coulomb infers; (1.) That in the contact upon the surface of the plate, the trial plane shares the electricity of only one of the two faces, which is that to which it is applied; (2.) That beyond a certain length of the plate, so considerable that the electricity shall be nearly uniform over the greater part of its surface, any prolongation has no sensible influence upon the ratios of the quantities of electricity accumulated at the extremities and at the centre, the first being always double the second.

To understand the full import of this remark, let AB be a
Fig. 11. plate whose length exceeds the limit just mentioned. Suppose the electrical state of the different points of its surface to be examined, and represented by the ordinates CE, PM, QN, AA', BB'. These ordinates will not differ sensibly from each other until we arrive within about an inch of one of the extremities, after which they will go on rapidly increasing through the remaining portion, so as to form the curve $A'M$ or $B'N$. Now, since the ratio of AA' to PM or to CE is the same in all plates whose length is very great in comparison with their breadth, and as the same constant ratio obtains for the intermediate ordinates, it follows that the curve $A'M$ or $B'N$ preserves the same form for all these plates, and is merely placed at the two extremities upon the uniform lamina, whose thickness is CE; and thus it is easy to foresee the electrical state of all plates of this description, when that at the centre is once known.

This rapid increase of the electricity towards the extremity is not peculiar to plates; it is found to take place generally in all elongated prismatic and cylindrical bodies; and it is more rapid according as they are more thin.

34. The tendency of electricity to the surface of conducting bodies, and the manner in which it distributes itself there, may be rendered evident by a very curious experiment. Let AB repre-

sent an insulated cylinder movable about a horizontal axis, and made to revolve by means of the glass winch *M*. About this cylinder is wrapped a thin metallic sheet *R*, which terminates in a semicircle, and is attached to a cord of silk *F*. This apparatus is made to communicate with an electroscope, composed of two linen threads *f*, *f*, supporting pith balls. The instrument being electrified, the threads *f*, *f*, diverge; we then gradually unrol the sheet of metal, lifting it off by the cord *F*, and holding it suspended in the air. As it is extended, we see the linen threads approach, indicating a gradual diminution of action. If the sheet is sufficiently long, compared with the electrical charge given to the apparatus, the divergence will diminish till it becomes almost insensible; but it will increase again, if, upon turning the winch *M*, the sheet of metal is again wrapped about the cylinder; and then the action of the threads becomes the same as at first, allowance being made for the loss occasioned by the contact of the air. Fig. 12.

Of combined Electricities, and induced Electricities.

35. We have thus far considered bodies as electrified by friction or communication. We come now to make known a class of phenomena in which the electrical state is produced without contact, and by the mere influence of electrified bodies at a distance.

We take a cylindrical conductor *B*, insulated in a horizontal position, the two extremities being hemispherical. We attach to it at small intervals linen threads, to which pith balls are suspended. After touching this conductor, to make it certain that it is not charged with electricity, we bring it toward the electrified body *A*, holding it by its insulating supports, and placing it always at such a distance from *A* that the electricity cannot be communicated by a direct discharge. We shall then observe the following phenomena; Fig. 13.

(1.) The threads placed at the extremities of the cylinder *B* diverge, and thus show that it is electrified.

(2.) This divergence goes on diminishing toward the middle of the cylinder, and there is a point at which there is no repulsive force whatever.

(3.) This unelectrified point varies in its position upon the cylinder, according as it is moved from or toward the electrified body.

(4.) If we present along the cylinder a pith ball, unelectrified and suspended by a thread of silk which insulates it, it is attracted throughout, except at the intermediate point of which we have just spoken.

(5.) But if this pith ball be electrified, it is attracted by one extremity of the cylinder and repelled by the other, which shows that they are charged with different electricities.

(6.) Indeed, if we touch these two extremities successively with a small insulated conducting body, and examine the electricity thus obtained, we shall find that at the extremity next to the electrified body *A*, it is of a different nature from that of the body *A*; and that it is of the same nature at the opposite extremity.

(7.) The signs of electricity cease if we remove the cylinder by its insulating supports, to a great distance from the electrified body *A*, or if we deprive the body *A* of its electricity.

(8.) With the exception of this last case, the body originally electrified loses no part of its electricity by the influence which it exerts. No part of its electricity is transmitted to the cylinder; for if we measure its electrical action before the cylinder is brought toward it, and after it is withdrawn, we find that it has suffered no loss, except what is naturally due to the mere contact of the air.

(9.) This constancy obtains only while it is beyond the influence of the insulated cylinder. For while it is near that, the action at its surface, especially if it be itself a conductor, is disturbed, as may be ascertained by means of the trial plane.

(10.) If, without touching the electrified body *A*, we remove and replace the cylinder several times, the same phenomena will be repeated each time without any change, except what arises from the diminished intensity of the body *A*.

The simple statement of these facts, leads us directly to the conclusions to be derived from them; (1.) Since the cylinder takes nothing from the electrified body, it must possess in itself the principles of the two electricities which are excited in it by the influence of this body; (2.) Since these two electricities disappear when the influence of the foreign body ceases, although they cannot escape into the earth, we infer that their proportions are such that, being left to themselves, they mutually neutralize each other; (3.) Finally, this neutralization must needs take place without destroying

them, for they reappear entire whenever we expose the cylinder to the influence of the foreign body.

36. We hence learn that the principles of the two electricities exist naturally in all conducting bodies, in a state of combination by which their effect is neutralized; this we shall in future call *the natural state of bodies*. We now perceive that friction, which seemed to be a means of creating them, serves only to disengage them from their combination, and to render one of them sensible by absorbing the other; and this is the reason undoubtedly why we constantly observe that the rubbing body and the body rubbed exhibit contrary electricities. Finally, since the simple influence of an electrified body, presented at a distance, forces these two electricities to separate, and to arrange themselves so that those of a different nature are the nearest to each other, and those of the same nature the most remote, in enunciating this fact, we are compelled to admit, *that opposite electricities attract, and similar electricities repel each other*, according to laws which we shall be able to determine by experiment. In this last instance, a body is said to be electrified by induction.

Thus, all the phenomena which we have described, become simple, necessary, and evident consequences of this general property; with the exception, perhaps, of one which may require some further elucidation. This is the momentary variation in the electrical action of the body *A*, while the cylinder is presented to it. But, since the free electricity upon the surface of one body acts upon those of other bodies, and destroys their combinations, at least in part, it is manifest that these electricities, being once set free, must in their turn act upon the body which liberated them, and change the electrical action of the several points of its surface, either by causing the free electricity resident there, to distribute itself in a different manner, or by adding to this electricity that which the body is capable of furnishing by the decomposition of its natural electricity, or finally by acting in both these ways at the same time.

37. These observations lead us to another important inference; in our first experiments, it may have been remarked that electrified bodies attract, or seem to attract, all light bodies which are presented to them, without its being necessary for this purpose to give them the electrical principle either by friction or communication.

But we must now suppose that this excitement takes place of itself, by the simple influence at a distance of the electrified body upon the combined electricities of the light substances which are presented to it. Therefore in this case, the observed attraction, whether it be real or apparent, actually takes place only between electrified bodies.

Moreover, the decomposition of the combined electricities is necessary in order that the attraction may manifest itself; for this attraction is so much the less lively according as the decomposition is more difficult, and ceases entirely if the decomposition be impossible. To be convinced of this, take two very fine threads of raw silk of equal length. Attach to them two small balls of equal dimensions, but of which one is of pure gum lac, and the other also of gum lac, but gilt or covered with tin-foil. These pendulous bodies being then placed at a small distance from each other, bring near them an electrified tube of glass or sealing wax; we shall see that the ball covered with metal, upon the surface of which the decomposition of the combined electricities is easily effected, will be much more readily and strongly attracted than the other, which does not begin to discover signs of electricity till after a certain time, when the decomposition has at length taken place upon its surface; and its electrical state continues even after it has been removed from the electrified body. The first ball, although covered with metal, also contracts in this way a durable electricity, because the resin it contains is impregnated with the electricity excited at the surface; and both the one and the other are favored in this respect by the contact of the air, which, on account of the influence of the electrified body, tends to take from each that one of the two combined electricities which is repelled by this body, while it has less power over the other, whose proper repulsive force is concealed by the attraction. Thus we remark generally, that insulated bodies which have been for some time submitted to the influence of an electrified body, come at length to have an excess of electricity of a nature opposite to that of this body, the effects of which appear after they are removed from its influence.

As we shall have frequent occasion for the results at which we have now arrived, we shall reduce them to a sort of theorem; thus,

When an insulated conducting body B, taken in its natural state, is brought near to another body A, electrified and insulated, the electricity upon the surface of A, exerting its influence upon the two combined electricities of B, decomposes a portion proportional to the intensity of its own action, and resolves this portion into its two constituent principles, repelling at the same time that of the same name with itself, and attracting that of the contrary name. The first withdraws to the part of the surface of B, which is most remote from A, while the second is collected on the part nearest to A. These two electricities having become free, act in turn upon the free electricity of A, and even upon its two combined electricities, of which a part is decomposed by this reaction, and separated if the body A is also a conductor. This new separation produces a new decomposition of the combined electricities of B, and so on till the quantities of each principle which have become free upon the two bodies, are put in a state of equilibrium by the balancing of all the attractive and repulsive forces exerted upon each other, in virtue of their different or similar nature.

We shall soon inquire into the conditions according to which this equilibrium is determined. At present we suppose this state established; and that we may continue to observe the development of the phenomena which result from it, we return to the instrument before used. Moreover, in order to render the statements as simple as possible, let us suppose that the electricity originally given to A is vitreous. Then if the conductor B is cylindrical, which we suppose, in order that the separation of the combined electricities may be more manifest, the part R nearest to A will be in the resinous state, and the more remote part V in the vitreous. Fig. 14.

Things being thus disposed, we touch the part V with a third conductor C, also insulated and in its natural state, which, being withdrawn, will be found to be charged with vitreous electricity, the linen threads placed at V upon the conductor B, collapsing at the same time, and those placed at R increasing their divergence. If, after this contact, we withdraw B from the vicinity of A, or if we touch A in order to deprive it of its electricity, we shall find B charged with resinous electricity only.

This is a very simple consequence of the influence exerted at a distance. Before the contact, the vitreous electricity of *B*, crowded into the part *V*, repelled the vitreous electricity of *A*, and attracted the resinous electricity developed in *R*; it therefore weakened the action of *A* upon *R*. By the contact of the third conductor *C*, we take away a portion of this electricity in *V*; and the action of *A* upon *R*, being less counteracted, becomes stronger. On account of this new increase of energy, there takes place in the conductor *B*, a new decomposition of the combined electricity, of which the vitreous part withdraws again to *V*, and the resinous to *R*. Then the whole quantity accumulated in *R* is necessarily greater than that in *V*, since this last was partially withdrawn by the contact of *C*. And thus, when we remove *B* from the influence of *A*, this vitreous electricity again becoming free, is not sufficient completely to neutralize the resinous in *R*, and we find the conductor *B* charged with an excess of resinous electricity. Owing to this inequality, the divergency of the threads, when under the influence of *A*, must be less in *V* than in *R*, as from observation it is actually found to be.

If we would carry this difference to the extreme, instead of touching the conductor *B* with an insulated body, which takes away only part of the electricity of *V*, we touch it with an uninsulated body, and thus suffer it to communicate for a moment with the ground. Then all the electricity collected in *V* will escape; and the threads suspended at this point will collapse entirely; but the threads at *R* will diverge still more than before, and we shall not diminish their divergency by touching again the extremity *V*. But if we remove the conductor *B* from the influence of *A*, the divergence will become much less.

This also is easily explained. When we permit *V* to communicate with the ground, all the electricity accumulated at this extremity, passes to the great mass of the earth, and its electrical action becomes insensible; or, if you please, it decomposes the combined electricity of the earth, atttacts the resinous with which it is neutralized, and repels the vitreous which distributes itself over the whole surface of the terrestrial globe. In whatever way we choose to consider it, there is no longer any free vitreous electricity in *V*. The vitreous electricity of *A* being now freed from this

resistance, exerts a stronger attraction for *R*. This requires a new decomposition of the combined electricity of *B*, of which the vitreous part passes off, as before, to the ground, while the resinous is accumulated in *R*; and so on, till the attraction of *A* for the resinous electricity is completely satisfied. But these decompositions, which in our reasoning we have supposed successive in order to explain how they are effected, take place instantaneously in those metallic bodies, which may be regarded as perfect conductors; and for this reason a single contact is sufficient to produce them completely. After what has been said, it is evident why *B*, being removed from the influence of *A*, manifests an excess of resinous electricity, and why this excess is still greater than in the preceding case.

38. We have thus far confined ourselves to rendering evident by experiment the action of *A* upon *B*; but we can also make the reciprocal action of *B* upon *A* manifest, either by touching the latter in different points of its surface with the trial plane, which would be the more exact way of proceeding; or by simply suspending at the extremity of *A*, the most remote from *B*, linen threads terminated with pith balls. We observe, in the first place, the divergence of these balls when the body *A* is insulated and removed from other bodies. Then, according as it is made to approach the conductor *B*, and there takes place in this a decomposition of its combined electricity, the linen threads on *A* gradually collapse, because the vitreous electricity, residing in this part of *A*, withdraws toward *B*, till at length by the continued approach of *A*, the threads lose their divergence entirely, as if the body *A* were in its natural state; and finally, there is developed in this part of *A*, a resinous electricity by the always increasing action of *R*, when the threads are seen to diverge again, but with a different electricity.

This succession of divergencies produced by contrary electricities, with a natural state intervening between them, will be still more easily observed upon the conductor *B*, if, instead of presenting it to *A* in its natural state, we first give it a feeble resinous electricity; for while it is removed from the influence of *A*, all the linen threads suspended from it, will diverge by reason of this electricity. But as *B* approaches *A*, and the action of *A* draws this resinous electricity toward the extremity of *B* nearest to *A*, we shall see

the threads at the other extremity gradually collapse, become parallel, and afterward diverge again in virtue of the vitreous electricity disengaged from its natural combination by the action of *A*, and repelled to this part of the conductor *B*.

For the sake of distinctness, we have supposed that the body *A* is charged with vitreous electricity. But if it were charged with resinous electricity, all the phenomena would be precisely similar, and in the enunciation of the facts, it would only be necessary to change throughout the names of the two electricities respectively.

39. Having thus recognised generally the attractive and repulsive powers belonging to the two electricities, and having made known their natural state of combination in bodies, their separation by influence at a distance, and the general consequences which result from these properties; we should next desire to subject these results to calculation, so as to be able to comprehend the facts enumerated in all their details, and to foretell, for instance, in the case of two bodies acting upon each other, the quantity and kind of electricity belonging to each point of their surfaces.

But as we have found that the effects of these reciprocal influences, so far as we have observed them, are exerted upon the electrical principles themselves, it is apparent that we shall not be able to trace them to their cause, except by determining the nature and manner of action of these principles; or, which to us is the same thing, by imagining from the observed phenomena, some determinate mode of action which will exactly represent the phenomena, and which admits of being verified, if not directly in its physical character, at least indirectly, but certainly, in its consequences.

Now if we consider the extreme facility with which the two electricities diffuse themselves in conducting bodies, and tend to the surface, where they are retained by the pressure of the air; if we consider also the perfect freedom with which they approach to or depart from each other, unite and separate without any loss of their original properties, it will be seen that the most probable view we can take of their nature is, to regard them as perfect fluids, the particles of which are impressed with attractive and repulsive powers, and which, in bodies where they can move freely, dispose themselves so as to be in equilibrium in virtue of all the interior and exterior forces which act upon them.

40. It is easy to perceive that each of these fluids must possess in itself a cause of repulsion by which its particles are driven from each other; for if we suppose a certain quantity of vitreous or resinous electricity to be introduced into a metallic sphere where its motions are free, we know that it will tend entirely to the surface where it will form a very thin stratum. If we augment the diameter of the sphere, the electrical stratum will retire farther and farther from the centre, diminishing always in thickness; finally, if we remove the pressure of the air entirely, the electricity will be completely dissipated. These effects certainly indicate a repulsive action exerted between electrical particles of the same nature; and all the phenomena in which the two combined electricities are separated from each other by influence at a distance, perfectly confirm this result, while they also demonstrate the existence of a reciprocal attraction between electricities of a different nature.

But the experiments which we have now related for the purpose of establishing the mutual repulsion of electric particles of the same nature, make known another important property, namely, the incompressibility of the electric principle, on the supposition that it is a fluid. For, if it were compressible, like the air, for example, when it is diffused through a conducting body, the mere effect of its own repulsive force would undoubtedly cause the greater part to flow to the exterior surface, where it would be condensed by the repulsion from within; and thus the density would go on gradually diminishing from this surface towards the interior of the body; but the inner strata, however much we suppose them to be rarified, would yet, strictly speaking, never cease; and thus we should always find electricity within the body in greater or less quantity, whereas we do not, by the most delicate tests, discover the least trace of it. It follows, therefore, that in order to reconcile this fact with the nature of the electric principle, we must suppose it incapable of being sensibly compressed; and different quantities being successively introduced into the same conducting body, and diffusing themselves there and flowing to its surface, must cause the electric stratum, situated at the surface, to take different thicknesses, which are always infinitely small, at least in all states to which we are able to reduce it.

41. We find also from the same phenomena, that these at-

tractions and repulsions diminish in force as the distance increases; but according to what law? Among the different laws which may be supposed to exist, there is one which perfectly represents all the phenomena; namely, that which supposes the force to vary in the inverse ratio of the squares of the distances. Adopting this law, the essential properties of the two electric principles are comprehended in the following proposition; *each of the two electric principles is an incompressible fluid, the particles of which, possessing perfect mobility, mutually repel each other, and attract those of the opposite principle, with forces varying in the inverse ratio of the squares of the distances.* Moreover, *at equal distances, the attractive force is equal to the repulsive;* this equality is necessary in order that the two combined electricities in unelectrified bodies may exert no action at a distance, as may be proved by experiment;
Fig. 15. take two discs of thin glass AB, $A'B'$, whose surfaces are ground very true, and which are about 4 inches in diameter; to each of them fix a handle CM of glass or sealing wax or any other insulating substance; then, having prepared a very sensible pendulum, consisting of a small pith ball suspended by a fibre of silk, as it comes from the silk worm, rub the discs against each other, holding them by the insulating handles; and without separating them, present them together to the pendulum. You will see that they exert upon it no attraction; but separate them and present them to it in turn, and they will each attract it. They are therefore mutually electrified by the friction; and one has acquired the vitreous and the other the resinous electricity, as may be proved by presenting them to a second very sensible pendulum, charged with a known electricity. But these electricities do not become manifest when the discs are in contact, for residing upon the two surfaces in contact, the distances of all their points from the pendulum is absolutely the same, and therefore the opposite actions which they exert to separate the combined electricities of the ball are equal; and thus their total resultant is nothing. We may also modify this experiment so as to make the compensation of forces progressive. For this purpose, after having separated the discs, we bring the electrified surface of one of them in contact with the pendulum. After the ball has taken the small quantity of electricity proportional to its magnitude, it is repelled. Keeping it in

this state of repulsion, we present the other face of the disc, as represented in figure 16; (for the electricity will act upon it with the same power through the thickness of the glass.) Then bring the second disc gradually toward the first, in the manner represented in the figure. As they are made to approach each other, we shall see the repulsion diminish and the small pendulum descend more and more, and finally, when the discs come into actual contact, they will together produce no effect upon the pendulum, but it will be driven off again when they are separated. These two electricities thus neutralized by their contact, represent to us the natural state of the combined electricities, with this difference only, that in conducting bodies, the two electricities are united to each other simply by their force of combination, and may be separated by the action at a distance of a free electricity; while in the glass discs, each of the electricities is retained by the resistance which the non-conducting nature of the glass opposes to the freedom of its motions. For this reason, the experiment which we have now described would succeed equally well with discs of gum lac or sealing wax, or even with one disc of a substance of this kind and one of metal. But it could not take place with two discs of a conducting nature; for then no resistance being opposed to the motion of the electricities, they would unite and combine anew as fast as they were disengaged by the friction.

Theory of Electricity.

42. In any branch of natural science, where the facts collected in the careful observation of the operations of nature, and by accurate and well-directed experiments, become sufficiently numerous and varied to show traces of general laws, it is the province of the philosopher to form a theory, which, by assigning adequate general causes, may embrace, under a few comprehensive theorems, all the various phenomena which observation and experiment have supplied. By such means, those who prosecute scientific researches are placed in a condition to foretell what will happen under any supposable physical conditions; and the accordance of the event with such predictions, supplies the most legitimate proof of the va-

lidity of the theory on the principles of which such predictions were made.

It has happened in almost every branch of natural science, that more than one theory has been propounded to account for the phenomena; and, in many cases, rival theories have maintained their ground, supported by a body of partisans, during the progressive advancement of the science under the increasing labors of those whose vocation is to observe and collect facts and phenomena rather than generalise them. No hypothesis can be expected to gain any general or permanent acceptance, which does not afford a satisfactory explanation of the more striking phenomena, and obvious appearances, for the explanation of which it has been proposed. In cases, therefore, where the community of science has been divided between two contending theories, more especially in modern times, when inductive science is so well understood, it ought to excite no surprise that both such theories afford explanations equally plausible and satisfactory for all the ordinary phenomena comprised in the department of science to which they extend. It is not, then, by the account which they render of these prominent effects that the claims of conflicting hypotheses can be decided. If they had not been adequate to the explanation of such appearances, they never could have obtained such an extensive assent as to raise any question respecting their validity. Such hypotheses can only be tested in two ways: *first*, by exacting from them a clear and consistent account of phenomena developed *after* the theory itself had been proposed, and which were not foreseen by those who propounded it; and, *secondly*, by deducing from it, not merely a *general* account of the phenomena which will be produced under any given physical conditions, but by exacting from it a rigorous *numerical* and *quantitative* estimate of the effects, and by comparing such estimate, so deduced from the theory, with the actual numerical and quantitative account as obtained from experiment and observation. If the discrepancy between the numbers and quantities furnished by the theory and by observation exceed the possible amount of the errors of observation, and still more, if the principles of the theory afford no means whatever of reducing the effects to numerical calculation, such theory must be rejected as insufficient. If, on the other hand, it be found that an hypothesis, capable of affording a clear

and satisfactory explanation of the general nature of all the phenomena, as well those which were known to its proposers, as those which observation and experiment subsequently developed; if it also supply the means, by calculation and reasoning, of predicting other phenomena to which experiment and observation have not yet been directed, and that the effects already produced under the prescribed conditions have been seen to be in strict accordance with such predictions; if, moreover, by the application of the principles of analytical calculation, the *numerical* and *quantitative* amount of *all* the phenomena are capable of being deduced from such hypothesis, and the difference between such numerical results and the actual numerical quantities obtained by observation and experiment, do not exceed the possible amount of the errors of observation; — then such theory must be regarded as proved, and ought, by the principles of inductive philosophy, to be assented to and received, until some phenomena shall arise of which it is incapable of giving a satisfactory account.

43. Two theories have been proposed for the explication of the phenomena of electricity. That which, until within a few years, has been most generally embraced in this country, originated with Dr. Franklin, by whose labors this department in physics has been so highly enriched. The other hypothesis belongs to Dufay; and, for convenience, has been made in this treatise the point of departure for describing and grouping together the facts of the science. Both these theories agree in ascribing the phenomena of electricity to a material substance, endowed with the most perfect fluidity, the molecules of which are distributed on the surfaces of bodies. The properties of a fluid are irresistibly suggested by all the most striking phenomena of electricity. The extreme facility with which electricity diffuses itself on conductors, its rapid escape when relieved from the pressure of the surrounding air, the perfect mobility with which its particles transfer themselves from conductor to conductor, and by which they combine and separate, all concur in suggesting the notion of fluidity.

If electricity be material, it must be conceived of as a rare, subtile, and highly active fluid: whose inertia compared with its elastic force is excessively small: obeying every impulse, internal or external, with the greatest promptitude; in short, a fluid whose

energies can only be compared with those of the etherial medium, by which in the undulatory doctrine, light is supposed to be conveyed. The properties of hydrogen gas, compared with those of the denser aëriform fluids, will, in some slight degree, aid our conception of the excessive mobility and penetrating activity of a fluid so constituted. Electricity, however, must be regarded as differing in some remarkable points from all those fluids to which we have hitherto been accustomed to apply the epithet elastic, such as air, gases, and vapors. In these, the repulsive force of the particles on which their elasticity depends is considered as extending only to very small distances, so as to affect only those in the immediate vicinity of each other, while their attractive power, by which they obey the general gravitation of all matter, extends to any distance. In electricity, on the other hand, the very reverse must be admitted. The force by which its particles repel each other extends to great distances, while its force of adhesion to other matter must be regarded as limited in its extent to such minute intervals as escape observation.

44. The conception of a single fluid of this kind, which when accumulated in excess in bodies, tends constantly to escape, and seek a restoration of equilibrium by communicating itself to any others where there may be a deficiency, is that which occurs most naturally to the mind, and was accordingly maintained by Franklin to whom the science of electricity is under great obligations for those decisive experiments which informed us respecting the true nature of lightning. Most electrical phenomena, if we confine ourselves to their general circumstances, may be explained on the supposition of a single fluid, diffused in a certain quantity through all bodies, and forming their natural state. An excess of this fluid is what we have called the vitreous electricity, and a deficiency, what we have called the resinous; hence result two new states of bodies, which the advocates for this system designate by the names of *positive* and *negative*. They admit also that the particles of the electric fluid mutually repel each other. But since experiment shows that bodies in their natural state exert no electric action upon each other, they are obliged to suppose that the electric particles are attracted by the proper matter of bodies. In fine, it has been shown by a thorough and rigorous investigation, that

this hypothesis will not account for an equilibrium without a new condition, viz: that the particles of bodies exert upon each other a repulsive action, sensible at great distances, like the electric influence itself, and varying with the distance according to the same law. Franklin, the author of this theory, employed it very ingeniously in explaining all the electric phenomena known in his time, and which till then remained insulated and scattered; but he did not perceive the apparently paradoxical consequences to which his hypothesis led. In the loose manner in which the theory was in his time applied, it was sufficient to explain in a general manner the limited body of phenomena then observed; and it was not until further observation and inquiry had multiplied the facts, and a more rigorous account of these facts was exacted, and it became necessary to reduce the theory to a strict mathematical form, that the necessity of this additional assumption of a repulsion between matter and matter at a distance, so opposed at first view to the most striking phenomena in nature, was felt. Æpinus was the first, who showed how the statical laws of such a fluid might be reduced to strict mathematical investigation, and who, by an exact analysis of all the forces which concur in producing the electric equilibrium, discovered the necessity of a repulsion between the material particles of bodies;* after him the celebrated Henry Cavendish was also led to the same conclusion; for he made this repulsion one of the essential conditions of an hypothesis respecting the nature of electricity, which he published in the Philosophical Transactions for the year 1771, and which is very similar to that of Æpinus.

Although such a repulsive force between the material particles of all bodies may, at first view, seem absolutely incompatible with the more general phenomena of the universe, and particularly with the law of the celestial attraction, yet it is not so in reality. For this repulsion, as Æpinus and Cavendish employ it, would be exactly counterbalanced by the mutual attraction which their hypothesis supposes to exist between the particles of matter and those of the electric fluid diffused through all bodies in their natural state; so that in fact, these two contrary causes would produce no effect

* *Tentamen Theoriæ Electricitatis et Magnetismi*, p. 39.

upon bodies while in this state, and they would in no way impair the effects of the universal attraction which is exerted between bodies, independently of their electricity. The theory of Franklin is perfectly reconcilable with the discovery of Newton. Gravitation is predicated of matter in its ordinary state, with its average share of electricity upon it. Masses and particles of such matter attract one another, it is conceded : whereas it may be equally true that bodies divested of their electricity would exert a repulsion upon one another. The researches of Mossotti on the forces which regulate the internal constitution of bodies amply justify this conclusion. Adopting with Franklin a single electric fluid, he has shown, as he thinks, that gravitation is entirely consistent with the supposition that the molecules of matter are repulsive to each other. He has supported this opinion by a mathematical investigation of the conditions of equilibrium, both for the molecules of matter and for the electric fluid. The results at which he arrived show that two molecules of matter, surrounded by their electric atmospheres, are mutually attractive when separated by a sensible distance : that the attraction increases on the approach of the atoms up to a certain point, where the attractive force attains its maximum, and beyond which the molecules are mutually repulsive. In this manner, gravitation, cohesion, the resistance of matter to compression, and the electrical laws, are various effects of the same forces acting under the different circumstances of quantity and distance : they are residual phenomena, or the uncompensated portion of the three great classes of forces which represent the action of electricity upon itself, of electricity upon matter and of matter upon itself.

Now, admitting such a state of things to be possible, most electrical phenomena may be accounted for, and their mutual dependence conceived and even foretold, not indeed particularly and numerically, but as to their general character. That it would afford a reasonable explanation of the ordinary attractions and repulsions, and the chief electrical effects upon bodies by induction, may be admitted ; for no theory which could fail in giving a reasonable account of effects so conspicuous, could have obtained any acceptance. It does not appear, however, in what way a theory, in which different kinds of matter must be admitted to exert different attractions for the electric fluid, can explain the distribution of elec-

tricity on the surfaces of conducting bodies, in a manner depending *solely on their form*, and not at all on their *chemical composition.* If different material substances have different attractions for the electric fluid, how does it happen that the distribution of that fluid on an oblong plate of metal, of given dimensions, will be the same, of whatever metal the plate be formed, or even though it be formed of pieces of various different metals connected together? Neither can that theory show why negative electricity, which it views as a deficiency or absence of the electric fluid, should, when developed on the surfaces of bodies, produce effects in conformity with the rigorous hydrostatical laws, which an elastic fluid would obey, whose molecules repel each other with forces which diminish in intensity as the square of the distance between them increases. If this theory of a single fluid fail in affording a reasonable explanation of such striking phenomena, its insufficiency becomes still more glaring when by its principles an attempt is made to calculate the depth of the electric fluid on bodies of various forms, brought under each other's influence in given positions. Thus, if two spheres composed of a conducting substance are brought into contact and electrified, and then separated, it will be found, that round the point of contact, on the smaller sphere, electricity will be diffused of a kind contrary to that with which the spheres were electrified; and this electricity will extend to a certain distance round the point of contact, beyond which the electricity diffused over the remainder of the sphere will be the same as that with which the two spheres were electrified. The theory of a single fluid cannot account for this general fact; still less can it enable us to compute the limits which separate the portions of the sphere electrified by the one electricity from that electrified by the other. On the other hand, the hypothesis of two fluids, observing the conditions by which that hypothesis is restricted, not only enables us to show that under these circumstances the development of a contrary electricity round the point of contact, and of the same electricity over the remainder of the sphere, is a natural and inevitable consequence of the properties, which, in this theory, are assigned to the two fluids, but it enables us to calculate with the most surprising precision the exact limits which, in any given position, separate the positive from the negative regions of the smaller sphere.

45. If we pass now on to the other theory of electricity, we have to consider two distinct fluids, each attracting the other, and repelling itself: but each, alike, susceptible of adhesion to material substances, and of transfer, more or less rapid, from particle to particle of them. These fluids in the natural, undisturbed state, are conceived to exist in a state of combination and mutual saturation: but this combination may be broken, and either of them separately accumulated in a body to any amount without the other, provided its escape be properly obstructed by surrounding it with non-conductors. When so accumulated, its repulsion for its own kind and attraction of the opposite species in neighboring bodies, tends to disturb the natural equilibrium of the two fluids present in them, and to produce phenomena of a peculiar description, which are termed *induced* electricity. Curious and artificial as this theory may appear, there has hitherto been produced no phenomenon of which it will not afford at least a plausible, and in by far the majority of cases, a very satisfactory explanation. It has one character which is extremely valuable in any theory, that of admitting the application of strict mathematical reasoning to the conclusions we would draw from it. Without this, indeed, it is scarcely possible that any theory should ever be fairly brought to the test by a comparison with facts. Accordingly, the mathematical theory of electrical equilibrium, and the laws of the distribution of the electric fluids over the surfaces of bodies in which they are accumulated, have been made the subject of elaborate geometrical investigation by the most expert mathematicians, and have attained a degree of extent and elegance which places this branch of science in a very high rank in the scale of mathematico-physical inquiry. These researches are grounded on the assumption of a law of attraction and repulsion similar to those of gravity and magnetism, and which by the general accordance of the results with facts, as well as by experiments instituted for the express purpose of ascertaining the laws in question, are regarded as sufficiently demonstrated. The mathematical problems involved in the application of the theory of two fluids to the explanation of electrical phenomena require for their solution the last resources of the most profound analytical researches of modern science. It would not be consistent with the object of a treatise like the present to enter into the details of such investigations. The language itself,

in which alone the general theorems of electricity must be expressed, would be unintelligible to the great majority of our readers. Much may be done to popularise mathematics, and more especially those parts of mathematics which express the laws of physical phenomena; but this advantage has practical limits beyond which it cannot be carried, and in the whole range of mathematical physics it would probably be difficult to find a portion of science which would more decidedly forbid any attempt at popular or elementary exposition than the results of the mathematical investigation of electrical phenomena. We shall not pretend, therefore, to deliver here even an abridged view of the splendid labors of Poisson in this department of physics.

We may remark, that whatever be the real nature of the electric principle, since the constitution which we have attributed to the two fluids gives rise to almost all the phenomena in number and kind which have been deduced by calculation, there is sufficient reason for admitting this constitution provisionally in our subsequent inquiries; for, from the proofs already given, we may affirm, that whatever be the actual nature of the electric principle, it must adapt itself to the same facts with the same exactness, and consequently must be susceptible of the conditions we have attributed to the two fluids, so that the facts may hence be deduced in a similar manner, and by similar formulas with those already employed. But new observations or new applications will serve, in a more advanced state of the calculus, to confirm or refute this theory, and to show whether it is the exact and general interpretation of all the phenomena, or merely the approximate and particular expression for those which have been hitherto submitted to it.

Theory of the Motions produced in Bodies by Electric Attraction and Repulsion.

46. At the outset of our inquiries into electrical phenomena, we discovered that two electrified bodies, when placed at a certain distance asunder, seem to attract or repel each other. It appeared afterwards that the attraction and repulsion take place only between the two electric fluids, and that the substance of the bodies does

not, by any law of affinity, partake of these motions. It becomes necessary, therefore, to examine how, and by what mechanism, these forces are transmitted to the substance of bodies, and made to produce in them the motions which we observe.

For the sake of simplicity, we shall confine ourselves, in the first place, to the consideration of two electrified spheres *A* and *B*, the one *A* fixed, the other *B* movable. Three cases may be supposed which it will be necessary to consider separately.

(1.) *A* and *B* non-conductors;

(2.) *A* a non-conductor, *B* a conductor;

(3.) *A* and *B* conductors.

47. In the first case, the electric particles are fixed upon the bodies *A* and *B* by the unknown force which is the cause of their non-conducting property. Not being able to quit these bodies, they communicate to them the motions which their reciprocal action tends to impress upon themselves.

The forces, then, by which motion may be produced, are; (1.) The mutual attraction and repulsion which the fluids of *A* and *B* exert upon each other; (2.) The repulsion of the fluid of *B* for itself. But as the mutual repulsion of the parts of a system can produce no motion in its centre of gravity, the effects of this latter action destroy each other upon the two spheres respectively, and no motion can result from it of one toward the other. We need take account, therefore, only of the first kind of forces. If the distribution of the electricity be uniform upon each sphere, each will attract or repel the other just as if its whole electrical mass were united at its centre, and the whole force of attraction or repulsion is proportional to the product of the whole quantity of electricity which they possess. This force transmits itself to the ponderable matter of the two spheres *A* and *B*, in virtue of the adhesion by which they retain the electric particles; and, on account of the two factors of which its expression is composed, it will be seen that it would become nothing if one or the other of the two spheres were not first charged with a foreign electricity. During the motion, it suffers no variation except that which arises from change of distance, because the two spheres, being supposed to be of substances strictly non-conducting, their reciprocal action can produce no new development of electricity.

48. In the second case, the sphere *B*, supposed to be of conducting matter, suffers a decomposition of its natural electricities by the influence of *A*. The opposite electricities which result from this decomposition unite with the foreign electricity communicated to this sphere, and they arrange themselves together agreeably to the laws of electric equilibrium; then the motion of *B* toward *A* may be considered in two points of view.

Let us suppose, in the first place, that without disturbing the electrical state of *B*, we spread over its surface an insulating wrapper, solid, without weight, and adhering to it throughout. The electricity of *B*, being unable to escape, will press upon the wrapper, and by this means transmit to the particles of the body the forces by which it is itself acted upon. Then the forces which act upon the system will be, (1.) The mutual attraction or repulsion of the fluid of *A* and the fluid of *B*; (2.) The repulsion of the fluid of *B* among its own particles; which, however, can produce no motion in the centre of gravity of *B*; (3.) The pressure of the fluid of *B* upon the insulating wrapper; but this pressure is exactly counterbalanced by the reaction of the wrapper, and no motion can result from it. The first force therefore, is the only one which we need consider.

When the distance *D* of the two spheres is very great compared with the radii of their surfaces, the decomposed electricities of *B* are distributed, according to calculation as well as experiment, nearly equally upon the hemisphere situated toward *A*, and that opposite to *A*. Then the actions which they experience from *A* are nearly equal and destroy each other. The effective force, therefore, results wholly from the quantities of foreign electricity communicated to the two spheres, and it is proportional to the product of these quantities. So long as the spheres are at a great distance from each other, this product and the attractive or repulsive force which it measures, vary only on account of the change of distance. But this is an approximation. For, strictly speaking, the electrical state of *B* varies as it approaches *A*, on account of the decomposition of its natural electricity produced by this sphere. Consequently the reciprocal action of the two spheres must also vary in a very complicated manner.

The supposition of an insulating wrapper without weight, serves

here only to connect the electric fluid with the material particles of the body B. This supposition may be considered as realized by the thin layer of air by which bodies are surrounded, and which adheres to their surface. But we may arrive at the same result in another way; in this case, it is necessary to consider the pressures produced upon the air by the electricities which exist in B in a state of freedom. In fact, these electricities, as well those which have been communicated to the body, as those which have been decomposed there by influence, tend toward the surface of B, where the air arrests them by its pressure and prevents their passing off. They dispose of themselves *under* this surface, therefore, in the manner required by their mutual action and the influence of the body A, supporting themselves against the air which prevents their expanding. But reciprocally, they press the air from within outward, and tend to lift it up with a force which is proportional to the square of the thickness of the electrical stratum at each point. When the spheres are at a great distance from each other, compared with the radii of their surfaces, the decomposed electricities of B press the exterior air in contrary directions with an intensity nearly equal, and their effects almost exactly destroy each other. There remains, therefore, only the effect of the foreign quantities introduced into the two spheres; and there results from it an excess of pressure directed according to the line of the centres, and proportional to the product of these quantities, that is, exactly equal to what the other method gave. It is evident, moreover, that this expression is subject to the same limitation, since the pressures produced by the electrical stratum against the exterior air must vary with the quantity of natural electricity decomposed in B by the influence of A, according as the two spheres approach each other.

49. The third case, where A and B are both conductors, is resolved upon precisely the same principles, either by imagining the two electrified surfaces covered with an insulating wrapper, and calculating the reciprocal actions of the two fluids which transmit themselves by this means to the material particles of the body; or by considering the pressures produced upon the exterior air by the two electrical strata, and calculating the excess of these pressures according to the line which joins the two centres. Only, in this case, the attractive or repulsive force of the two spheres will vary,

according as they approach each other, not only on account of the consequent difference in the intensity of the electrical action, but also by the progressive decomposition of their natural electricities which will take place in the two conducting bodies *A* and *B*.

The results to which we have now arrived would still hold true if the spheres *A* and *B* were both free to move toward each other; for without disturbing their reciprocal action, we may always impress on either of them its motion in a contrary direction, and this would reduce it to a state of rest, and refer the problem to the case which we have considered. We have taken bodies of a spherical form, because we are able to perform the calculations which give, in each case, the values of the attraction. The same reasoning will apply equally to all cases of attraction.

50. Let us consider, for example, the phenomena which are presented by an electrical pendulum drawn from a perpendicular by the action of an electrified tube. For the sake of distinctness, let us suppose this pendulum to be formed of a small pith ball suspended by a thread of silk *CS*, and charged with *vitreous* electricity. As long as the ball is withdrawn from all foreign influence, the electricity will dispose of itself *under* the surface in a very thin spherical stratum, of an equal thickness throughout; and consequently, the pressure which it will exert upon the exterior air will be equal also throughout, since it is at each point proportional to the square of the thickness of the stratum. The ball will therefore be less pressed by the exterior air than if had no electricity at its surface, but it will be equally so throughout, and consequently will have no motion in any direction. Fig. 17.

Suppose now that at some distance from its surface, a tube of gum lac or sealing wax is presented, electrified *resinously;* a portion of the natural electricities of the ball will be immediately decomposed. The resinous part will recede from the tube, and the vitreous part will tend toward it. This last motion will take place also in the foreign vitreous electricity, which was at first spead beneath the surface of the ball. The pressure upon the air, which is always proportional to the square of the thickness of the electrical stratum, will be most powerful on the side toward the tube; and consequently the atmospheric pressure, which was before equal over the whole surface, will become comparatively more powerful on the

opposite side. This excess of pressure will therefore urge the ball toward the resinous tube; and if we wish to retain it in its place by another thread of silk CS', acting in the direction opposite to this tendency, CS' will sustain all the effort produced by the difference of pressure.

Let us suppose now that the thread is cut. The ball will yield to the force exerted upon it, and the insulating thread CS which supports it will be drawn from a perpendicular position. But this deviation will have a limit; for the weight of the ball, which, in its first position, was supported by the point of suspension S, is
Fig. 18. only partially supported by it in the oblique position SC'. Indeed, if we represent the effort of this weight by the vertical line $C'P$, we may decompose it into two other forces, one $C'Q$ in the direction of the thread produced and which is destroyed by the resistance of this thread, the other $C'R$ perpendicular to the thread and tending to bring back the ball to the lowest point. Now this second force will evidently increase with the angle CSC'; and consequently it will tend so much the more to make the ball descend as it is farther removed from a perpendicular. Consequently, in each position of the tube, the deviation of the thread will be such, that the excess of atmospheric pressure, tending to make it rise, shall be equal to the decomposed gravity which tends to make it descend.

51. We have supposed the tube and the ball to be charged with opposite electricities; if the electricities were of the same nature, they would repel instead of attracting each other. The pressure of the electricity of the ball against the exterior air would be greatest on the part most distant from the tube, and accordingly it would make an effort to depart from the tube.

52. We have thus considered what generally takes place; but in certain cases a phenomenon occurs which appears at first view entirely to contradict the above reasoning. On bringing two bodies, similarly electrified, toward each other, the repulsive force is found to diminish, and, the bodies being brought still nearer, it is finally changed into attraction. This takes place ordinarily when one of the bodies is very small compared with the other and feebly electrified; for example, in the case where the pith ball of the electrical pendulum, is charged with resinous electricity, and a large tube of

sealing wax, also electrified resinously, is gradually brought nearer and nearer. But far from being an exception to our theory, this phenomenon is in fact a consequence of it. In proportion as the tube, on the approach of the ball, repels the resinous electricity which was first given to it, it decomposes a much greater part of its combined electricities. It repels the resinous which goes to join that first given to the ball, and attracts the vitreous toward itself. If there were only these two decomposed electricities on the surface of the ball, it would evidently be attracted toward the tube; and this attraction would increase as the distance diminished, and the tube became more highly electrified; and there would be no limit to this increase of attraction. But it is not so with the repulsion which, on account of the quantity of resinous electricity at first given to the ball, can increase only with the diminution of the distance. If, therefore, its force at a certain distance is less than the attraction owing to the progressive development of the combined electricities, the latter force will prevail, and the ball will approach the tube. We thus perceive that the phenomenon depends on the relative proportions of electricity at first given to the ball and tube; and without being able to assign these proportions, we see that the change from repulsion to attraction will take place the more readily and at a greater distance, according as the tube has more electricity and the ball less; and thus, if the distance is fixed, the repulsion and attraction will depend entirely on the ratio which subsists between the quantities of electricity.

This may be illustrated by an experiment represented in figure 19, in which an insulated metallic cylinder communicates with the prime conductor of the electrical machine. At the end of the cylinder a small pith ball is suspended by a silk thread, and its retreating beyond a certain distance is prevented by another thread attached to the cylinder. The cylinder is at first feebly electrified. The ball is attracted, touches it, and is then repelled. The electricity of the cylinder being increased, the ball is again attracted; and thus it is alternately attracted and repelled agreeably to our theory.

To give another example of the same principle, let us consider the motions of the little circle of gilt paper, which is attached to the needle of the electroscope or of the electrical balance. Let

us suppose that to this circle, charged with electricity of a certain kind, is presented, at some distance nearly parallel to its surface, another small circle fixed and electrified, and let this second circle for the present be considered a non-conductor, that the electricity distributed over its surface, may not be displaced.

When only the movable circle is in the balance, the electricity will distribute itself over its two faces in the same manner, and in equal proportions, on account of their symmetry. The lateral pressures against the exterior air are consequently equal, and no motion can result from them. But, when this electricity is subjected to the influence of the fixed circle, it will be attracted or repelled, and the pressure exerted against the air will become unequal upon the two faces. If it is attracted, its pressure upon the air is increased on the side toward the fixed circle; if it is repelled, the reverse takes place. And thus, in the first case, the excess of atmospheric pressure will impel the movable circle toward the fixed circle; and in the second, the motion will be in the opposite direction.

53. We have thus far considered surfaces of such forms that the electricity being left to itself, must evidently be distributed upon them symmetrically, and produce equal pressures upon the opposite parts. In this case the body will evidently remain at rest, unless exposed to the action of some foreign force. But although it is more difficult to recognise this compensation in bodies of less simple forms, it is not less certain that it actually takes place in them; for it is a familiar principle in mechanics that the reciprocal actions of the parts of a free system, cannot impress upon it any motion of translation, or of rotation about its centre of gravity.

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Fig. 20.

This would not be the case if the electric fluid could escape from some part of the body. Take, for example, a needle AA of thick wire, either of brass or iron, and let the two ends be bent in opposite directions, perpendicular to its length, and let them terminate in sharp points. At the centre C make a small hole, and adjust to it a conical cap, and place it upon a pivot CP so that the needle may turn horizontally. Let the foot of the pivot P be screwed to the extremity of the conductor of an electrical machine. No electricity being excited, the needle will remain at rest in its position, but if the machine be put in action, the needle will imme-

diately begin to turn, and with increasing rapidity as if it repelled the air by its points.

To understand this phenomenon distinctly, let us suppose that the needle, after being electrified, is covered with a small insulating wrapper without weight, and that it is suspended freely in a vacuum, by a thread of silk which permits it to turn freely about its centre *C*. In this case, the pressures produced at the surface of the electrical stratum, are exerted against the insulating wrapper; but according to the mechanical principle above referred to, they will produce in the system no motion of rotation about its centre of gravity, and all the pressures being decomposed in any direction, will mutually destroy each other on the opposite sides. Now let us suppose that at a certain part of the needle, either the point or any other part, we remove the insulating wrapper, so that the electricity may escape through this aperture; then the pressure at this part being nothing, the opposite pressure will act without a counterpoise, and cause the needle to turn in the direction in which the force is exerted.

The result could scarcely take place in an absolute vacuum, because the electricity of the stratum would be instantly dissipated when the insulating wrapper was perforated; but it may be obtained in the free air; it is only necessary to sharpen the points of the needle to such a degree that the electricity accumulated there, may overcome the atmospheric pressure. In this case, the air serves as a wrapper, and the aperture is made by the electricity itself; whereas, in the other case, we supposed it to be made artificially. The phenomenon would be precisely similar, if the needle, instead of being electrified, were a hollow vessel, filled with water or mercury, and its extremities, being bent and pointed, were two little canals whose orifices had been formed by the pressure of the fluid. The pressure then becoming nothing at these orifices, that which is exerted on the opposite element of the interior surface, would impel the needle, and thus cause it to turn in the opposite direction.

54. In this case, if we take the product of the masses into the velocities of all the liquid particles which escape, the product will be constantly equal to the sum of the products of the masses into the velocities of the other parts of the needle, and of the liquid which turns with it in the opposite direction. The same equality

must, thesefore, obtain in the motion of the electrified needle; but the mass of the electrical particles is absolutely insensible, since the most highly electrified bodies do not appear to have their weight increased by a quantity capable of being detected by the nicest balances; it follows, then, that the velocity of these particles must be infinitely great; and no example is, perhaps, better fitted to give us a just idea of this velocity.

Before we were made acquainted with the true laws of electrical equilibrium, it was not known by what means the attraction and repulsion, which actually take place between electrical particles, could transmit themselves to the material particles of bodies; and this effect was vaguely designated by the word *tension*, which represented the electricity as a spring placed between the electrified bodies, and tending to make them approach to, or depart from each other. The details into which we have now gone, serve to explain how this transmission of force takes place, by means of the pressure which the electricity exerts upon the surrounding atmosphere, or generally upon the obstacles which oppose its dispersion.

Of the Construction of Electrical Machines.

55. It has been apparent from our first experiments, that to render electrical phenomena conspicuous, it is necessary to apply the friction to surfaces of some extent. We accordingly make use of a large glass plate or cylinder fitted to turn against one or more rubbers, by means of a winch; and provided with an insulated metallic body placed near it, to receive the electricity, as it is developed, and to transmit it to other conductors, also insulated, as the experiment to be performed may require. But, knowing as we now do, that several bodies, thus electrified, exert always a mutual action upon each other, we have to inquire what is the best arrangement that can be given to the several parts of the apparatus; of what substance ought the rubber to be; what should be the form of the prime conductor and the other conductors; what the form, substance, and dimensions of the insulating supports, in order that they may respectively answer their purpose in the best manner. These important questions we shall answer very briefly.

There are three principal things to be considered; namely, the plate, the rubber, and the conductors.

56. Let us first consider the rubber. Whatever may be its substance, it is necessary, in order that it may produce an extensive and continued friction, that it should exactly fit the surface of the plate or cylinder, and that it should press it in a great number of points. Nothing is better adapted to this purpose than cushions stuffed with hair, and covered with simple leather, which are pressed by a spring against the surface of the glass. The leather alone, thus rubbing upon the glass, excites but little electricity. We obtain it much more abundantly by covering the cushions with a dry amalgam of mercury, zinc, and tin triturated together; so that the amalgam is in fact the rubber, and the glass the body rubbed.* If we insulate the cushions during the friction, and examine the electricity acquired by the glass, we shall perceive that it is vitreous; consequently the cushions take the contrary electricity, that is, the resinous, as may be easily shown. But in the ordinary use of the machine, we must be careful not to insulate the cushions; on the contrary, they must be made to communicate with the ground by a metallic conductor; for we thus obtain the electricity much more copiously.

This is always observed in the development of electricity by the mutual friction of any two bodies. The excess which each of them acquires is always much more sensible when the other communicates with the ground than when they are both insulated. The circumstance is of great importance, because it seems to relate to the manner in which the two electricities are developed by friction. But, for the same reason, it is difficult to be explained, because our theories apply only to electricity already excited, and are as yet but

* Mr. Singer, a late English electrician, who wrote a complete treatise on electrical instruments, recommends, as the best amalgam, a compound of two parts, by weight, of tin, four of zinc, and seven of mercury; the mercury to be heated by itself a little above 212° and poured into a wooden box, to which the proper proportions of zinc and tin, in a state of fusion, are to be added. The box is then to be closed, and briskly shaken to unite the ingredients as perfectly as possible. When the whole has become cold, it is to be pounded in a mortar and reduced to a fine powder; this powder is then mixed with a portion of hog's lard just sufficient to give it the consistency of paste.

little advanced with respect to electricity in its state of disengagement from bodies. We can therefore only enunciate the fact as it presents itself in the experiment, and deduce from it the mechanical conditions to which the development of electricity is subject. For this purpose, let us imagine, in the first place, two insulated bodies *A* and *B*, which being rubbed, the one against the other, in their natural state, acquire, the one a quantity $+ e$ of vitreous electricity, the other a quantity $- e$ of resinous electricity. I give the negative sign to the latter, to indicate that being added to the other, it neutralizes it. It is undoubtedly the nature of the two surfaces, and the power of the friction which determine this proportion between the spaces and the quantities of electricity which attach to each of them; of the nature of the mechanism by which this phenomenon takes place we are entirely ignorant. But the two electricities $+ e$ and $- e$ being once disengaged from their combination, there is no doubt that they preserve their individual properties, so as to exert their own repulsive force and mutually attract each other. In virtue of their own repulsion, the electricity $+ e$, developed upon *A*, tends to spread itself over *B*, at the points of contact; and reciprocally, the resinous electricity $- e$, developed upon *B*, tends to spread itself over *A*. This double tendency is also favored by the mutual attraction which $+ e$ and $- e$ exert for each other, and in virtue of which they endeavor to reunite. Since this diffusion and union do not take place, it follows that the unknown power which disengaged the two electricities $+ e$ and $- e$ from each other, and separated them, fixing one upon each body, should act also after this separation and with sufficient energy to keep them separate in spite of the two causes which conspire to make them unite. Now it appears that this action of rubbing takes place only at the surface in contact, so that it does not prevent either of the two electricities $+ e$ and $- e$ from spreading itself over the surface of the body upon which it resides, with the degree of freedom which belongs to the greater or less conducting power of this body. For if *B*, for example, be a conductor, and it be made to communicate with the ground by different points of the surface in contact, its electricity $- e$ will disappear, and *B* will return to the natural state, without the body *A*, on that account, losing its excess $+ e$; this is constantly seen when we rub an insulated body *A* against a

body B not insulated. Now it is very evident that in this state of things, the friction developes and maintains upon A a greater quantity of electricity than it would do if B were insulated. For, in the first case, if A took $+ e$, and $B - e$, in order to retain $+ e$, it would be necessary to overcome, besides its own repulsive force, its attraction to $- e$; whereas the latter force does not exist when $- e$ has passed off into the ground. For a similar reason, if the same body A is successively rubbed against two insulated conducting bodies B and B', both of the same nature, and presenting surfaces of the same kind, but of unequal extent, the larger will give a greater quantity of electricity to A; for the disengaged electricity which may fix itself upon B or B', being spread over the whole surface of these bodies, it will form a thinner stratum, with an equal quantity on the body of the larger bulk, and therefore the proper repulsive force of this electricity, at the surface in contact, will be less on this body than on the other; and hence it follows that the electricity can, in this case, be maintained in a greater quantity in a state of separation.

57. Besides these general conditions, the friction of the plate of the electrical machine against the insulated cushions, is attended with a circumstance which renders the effects produced much more feeble than when the cushions communicate with the ground. It consists in this, that the different parts of the plate which present themselves successively in their rotation to the rubber, have previously passed before the prime conductor, where the vitreous electricity which they had acquired is entirely or almost entirely neutralized; and thus they are nearly in their natural state when they come again between the cushions.* These different parts,

* The way in which this neutralization takes place, is very evident. The parts of the plate which arrive charged with vitreous electricity before the prime conductor, decompose by influence its natural electricities, repel the vitreous and attract the resinous in the points next to the plate. There, this resinous electricity, on account of the form of these points, acquiring a great repulsive force, breaks through the layer of air which separates it from the plate, and goes to neutralize the vitreous electricity adhering to it. The same effect would also take place, although less perfectly, if the extremity of the prime conductor nearest the plate, instead of being armed with points, had only an angular form, so that the escape of the electricity might easily take place.

therefore, represent so many insulated bodies A, all of the same nature, and in their natural state, which are rubbed successively against the same insulated body B. Now when the repetition of this friction has developed in B, the maximum of electricity $-e$, which can be maintained upon this body in contact with A, notwithstanding the repulsive force which this electricity possesses, it is manifest that new friction with other bodies A, cannot produce in B any new development of electricity. For if a new quantity $-e'$ should be developed and should unite itself with $-e$, the whole repulsive force $-(e+e')$ would overcome the resistance which opposes its diffusion over the surface in contact; and thus the new quantities of decomposed electricity would be immediately recompounded. Such must also be the result of the continued friction of the plate of the electrical machine against the cushions when they are insulated. The parts of the plate which first present themselves immediately develope in the cushions all the electricity which can be maintained upon them under the influence of the friction; after which the contact of the succeeding parts produces none, and the development of the electricity ceases, so that the plate no longer offers any thing to be neutralized to the prime conductor, whatever number of turns it may make. On the contrary, if the cushions communicate with the ground, and are thus constantly maintained in their natural state, the parts of the plate as they return successively, after being discharged by the prime conductor, are together with the cushions in the same state as at the first contact. They may therefore produce again in the cushions the decomposition of the natural electricities, become charged with a portion of the vitreous necessary to an equilibrium in this case, and come again to be neutralized by passing before the prime conductor, whence this electricity spreads itself over the secondary conductors, upon the surface of which it distributes itself according to the laws of electrical equilibrium; and this continual development of electricity ceases only when the whole quantity thus spread through the entire system of conductors, has acquired such a repulsive force that its action upon the part of the prime conductor nearest the plate, shall equal the opposing action exerted by the electricity, also vitreous, adhering to the parts of the plate presented to the conductor. It is then useless to continue the motion of the

machine; the charge of the prime conductor does not increase; or at most, it only acquires what is necessary to replace the waste occasioned by the air coming in contact with all the electrified surfaces of the plate and conductor.

This minute analysis of the phenomena of the electrical machine will suggest to us several important particulars by which its construction may be improved.

58. (1.) It is necessary that the parts of the glass which have been successively rubbed, should come before the conductor with the least possible loss of the electricity they have acquired. For this purpose, we attach to the rubber pieces of oiled silk or gummed taffeta, extending over the surface of the glass in the direction of the motion. After the glass is electrified, these strips adhere to its surface, and preserve it from the contact of the air till it has come near to the prime conductor.

(2.) It is necessary that the prime conductor should have as many branches as there are rubbers. We usually employ two Fig. 21. rubbers F and F', each of which comes in contact with both surfaces of the plate. They are placed at the two opposite extremities of the same diameter of the plate; and in order to establish with certainty their communication with the ground, the back part of each rubber consists of a piece of metal communicating with the two metallic branches AM, AM', which depart from the axis of rotation AA' also metallic. We have then only to connect this with the ground; for this purpose we attach to it a chain extending to the floor of the room, or, which is much better, communicating by means of a system of conductors with a water pipe or well. The prime conductor consists also of two branches CB, CB', the parts of which nearest the plate are armed with points for the purpose of discharging more easily the resinous electricity developed there by the vitreous influence of the parts of the plate successively presented to them. But the opposite extremities of these branches we never arm with points which would rapidly dissipate into the air the electricity acquired by the conductor; on the contrary, they are made to terminate in a large ball. Still a conductor thus terminated would be saturated with a moderate quantity of electricity. On this account it is made to communicate with a system of insu- Fig. 22 lated conductors, formed of long and narrow cylinders suspended

parallel to each other. Experiment and theory concur to show, that where the lengths and diameters of these cylinders are in proper proportion, this arrangement is best adapted to obtain large charges with but feeble intensities. It has this advantage also, that when we come to turn the plate or cylinder, we can cut off the communication between the prime and secondary conductors; for by this means we prevent the dissipation of the accumulated electricity which would rapidly escape by the points of the prime conductor, when the electricity of the plate, not being renewed, should cease to repel it.

It is evident that these changes in the communication ought not to be made by the direct contact of the hands of the experimenter, but by means of metallic rods attached to insulating handles. When only a momentary communication is required, we usually
Fig. 23 give to these rods the form of two circular arcs AC, $A'C$, turning on a hinge about the centre C, and each provided with an insulating handle M, which ordinarily is a rod of glass covered with gum lac. We take one of these rods in the left hand, the other in the right; then opening or closing the angle which they form, we can augment or diminish at pleasure the distance AA' of the two extremities of the arc, and adapt it to the distance between the two conductors which we wish to connect. This instrument is called an *exciter*, because it in fact serves to excite sparks between one conductor and another. The instrument represented in figure 24 answers the same purpose, although it is generally used to discharge jars or batteries, and is hence called a *discharger*. We also employ, as means of communication, metallic chains and cords which are suffered to hang from one conductor to another, and which are easily removed with tubes of glass when we wish to cut off the communication.

59. After determining the best forms for all the parts of an electrical machine, it only remains to say a word respecting insulation. It is plain that the insulation of the prime and secondary conductors ought to be as perfect as possible, that they may preserve for a long time the electricity which has been communicated to them. For this purpose, the supports should be as long and thin as consists with convenience and stability. Those of the prime conductor are usually glass pillars. They should be varnish-

ed with gum lac, because this gum insulates much better than glass, and is less likely to contract moisture. The secondary conductors may be suspended from the ceiling by silk cords; and it would be well, in this case, if the upper part of the cords were terminated by a cylinder of gum lac. As to other particulars, we proceed according to the principles laid down in the articles on conductors.

60. We have thus far supposed the rubbers to communicate with the ground, and the conductors to be insulated. In this case the electricity acquired by the conductors is vitreous. But we may also give them the resinous electricity. For this purpose, we make the branches CB, CB' of the prime conductor movable about the axis CC', and also the two branches AM, AM', which connect the rubbers with the ground. If we would obtain the resinous electricity, we turn these branches, as represented in figure 25, so that those of the prime conductor, which are insulated, shall touch the pieces of metal on the back of the rubbers, respectively, and those which before communicated from the rubbers to the ground are to be placed opposite to the rubbed surfaces of the plate. Then the vitreous electricity acquired by the plate is neutralized in a degree by the resinous electricity thus developed by influence in the branches AM, AM'; and, on the contrary, the prime conductor retains all the resinous electricity which is developed upon the rubbers. With this disposition of the instrument, it is necessary that the points with which the branches of the prime conductor are armed, should be disposed in such a manner, as to be opposite to, or in contact with, the rubbers, in order that their resinous electricity may pass into the system of conductors, either immediately and by contact, or by influence. Moreover, the supports which sustain the cushions and which are usually attached to the frame work of the machine, ought, in this case, to be of an insulating nature, and so arranged as to produce the most perfect insulation. It is also important to be able, as we have supposed, to bring before the glass plate the two metallic branches AM, AM', which communicate with the ground, in order to neutralize all the vitreous electricity with which the surface is covered when it comes from the rubbers; for, if it preserved this electricity, it would develope none anew when it passed a second time between the cushions, and the charge of resinous electricity which the conductor might acquire, would be much less.

*Of Electroscopes.**

61. *Electroscopes* are instruments destined, as their name imports, to discover the smallest quantities of electricity. We have
9. already spoken of that of Coulomb, which is a true electrical balance suspended by a thread of silk as it comes from the silk worm. Other electroscopes are also founded on the general principle of the repulsion which takes place between bodies charged with similar electricities; and their greater or less sensibility depends on the lightness and facility of motion of the substances employed to manifest this repulsion. These are usually two long light pieces of straw,
Fig. 26. or two slips of gold leaf L, L', suspended parallel and very near each other, by means of two very fine pieces of wire that hook into the rings q, a', formed in a common stem or rod, also metallic, which is terminated by a knob. By means of this continued communication, all the electricity given to the rod T is spread over the wires, and thence over the straws or leaves, which immediately manifest it by diverging from each other. But since the portion communicated is in fact all which is indicated, it must be evident that the apparatus will be the more sensible, according as these slips are lighter, more free in their motion, and according as the rod T, which communicates the electricity, retains a less portion of it upon its own surface. For this reason, it is necessary that the stem should be thin and the knob small, though of a size much greater than the stem. To prevent any motion from the air, and to screen it from accidental injury, the whole apparatus is enclosed in a square glass
Fig. 27. case, the neck of which is covered with gum lac that the insulation may be more perfect. The summit only of the stem appears above the glass, and this admits of being turned so that the slips shall diverge parallel to one of the faces upon which is traced a small graduated arc, to measure the amount of the divergence. It is evident that a greater or less divergence will indicate a greater or less degree of electricity; but as the tendency of gravity to bring the slips back to a vertical position, augments in proportion as they be-

* Usually called *electrometers* in English treatises on Electricity.

come more oblique, it is manifest that the repulsive force which supports them is not simply proportional to their divergence, but follows a law less simple, depending on the weight of the slips and their figure; and consequently the parts of the graduated arc, supposed equal among themselves, do not represent equal degrees of electricity. Therefore, when it is proposed to measure equal degrees, it is necessary to have recourse to the balance of Coulomb or to his electroscope, which alone possesses the double advantage of indicating the smallest electrical forces and of measuring them at the same time.

62. We can communicate to electroscopes of whatever description either the vitreous or resinous electricity, by touching the exterior knob of the stem with an insulated conductor charged with this kind of electricity. But there is another method equally suited to this purpose, which it may be well to explain, since it requires only a tube of glass or sealing wax, or other electric, which, on being rubbed with a proper substance, produces a known kind of electricity.

Let us suppose, for example, that a stick of sealing wax is used, Fig. 7.
and that the electroscope is that of Coulomb. The circle of tinsel *C* being in contact with the fixed ball *A*, we rub the sealing wax with a cat skin, and present it to the exterior knob *B* of the metallic stem *AB* at some distance; the needle *SC* is immediately repelled. The repulsion continues as long as the sealing wax is presented. If it be brought nearer to the knob, the needle is driven to a greater distance; if it be removed further off, the needle approaches the fixed ball; if it be entirely withdrawn, the needle returns and touches the ball, and remains in contact with it at its point of rest.

All these phenomena are to be referred to the case of influence exerted at a distance. The electricity of the stick of sealing wax is resinous. It decomposes the combined electricities of the stem *AB* and of the fixed ball *A*; it attracts the vitreous into the exterior knob, and repels the resinous into the fixed ball and the circle *C* of the tinsel which touches it. This circle is therefore repelled from the ball, since it is electrified in the same way. If the sealing wax is brought nearer, the decomposition of the combined electricities increases; the resinous electricity of the fixed ball becomes stronger,

and therefore the circle *C* is driven farther off. The contrary takes place if we remove the sealing wax. If it is taken away entirely, then the stem and the fixed ball are abandoned to their own proper forces, and their decomposed electricities again unite; but they cannot be neutralized completely, and the resinous electricity is too feeble by whatever the tinsel has taken away. The stem and fixed ball, therefore, remain charged with a small excess of vitreous electricity, corresponding to the resinous electricity of the tinsel. There ought, then, to remain some attraction, and it is only at the moment of contact that the union is completed.

63. This being well understood, nothing is more easy than to communicate to the tinsel and to the fixed ball a durable state of vitreous electricity.

For this purpose, touch the exterior knob of the stem with the finger, and present at a distance the excited sealing wax; then withdraw the finger, and *afterward* the sealing wax. During the contact, the influence of the sealing wax decomposes a portion of the natural electricities of the finger and the stem. This influence drives off the resinous electricity into the ground on account of the free passage which is afforded by the finger; and it retains the vitreous, which it attracts into the part nearest to the stick of sealing wax; so that if the stem be long enough, the tinsel placed at the other end will not be repelled. When the finger is withdrawn, this vitreous electricity can no longer escape; and when the sealing wax is withdrawn, it remains free upon the surface of the stem and fixed ball; and then the tinsel is repelled. It is necessary to withdraw the finger before the stick of sealing wax; otherwise the excess of vitreous electricity would escape into the ground; or, which amounts to the same thing, this excess would be neutralized by resinous electricity from the ground, and every thing would return to its natural state.

As a proof that this excess of electricity is really vitreous; observe the motions of the tinsel. Since, according to the disposition of the apparatus above supposed, it is not repelled till the moment when the sealing wax is withdrawn, it must have the same electricity as the fixed ball. Bring the sealing wax again toward the exterior knob nearer than before; it will attract toward it the vitreous electricity; and producing, moreover, a decomposition of the

natural electricities, it will repel the resinous into the fixed ball. The circle of tinsel will immediately return toward this ball; and if we do not immediately withdraw the sealing wax, it will come into contact. This approach under the influence of the sealing wax is the sign by which we may recognise all the cases in which the tinsel and the fixed ball are charged with vitreous electricity. By proceeding in the same way with a tube of glass rubbed with cat skin, or with woollen cloth, the tinsel and the fixed ball become charged with resinous electricity.

64. But the same effect may also be produced with sealing wax. For this purpose, take a small glass tube *t t*, at the extremity of Fig. 28. which attach perpendicularly, by means of soft wax, a wire *ff*, 8 or 9 inches in length. Touch the exterior knob of the electroscope with the insulated wire, placing it in such a manner that it shall become, as it were, the continuation of the stem *AB*. Then present at some distance the stick of sealing wax, and withdraw first the wire and afterward the sealing wax. The stem and the fixed ball will be charged with an excess of resinous electricity; for, by the disposition of the several parts of the apparatus, the vitreous electricity, which is decomposed, is almost entirely attracted into the wire *ff*, nearest the sealing wax. Therefore this wire must have an excess of vitreous electricity, and thus, by its influence, cause the stem and the fixed ball of the electroscope, to possess an excess of resinous electricity.

What we have now remarked may be easily verified by the motions of the tinsel. For when we remove the stick of sealing wax, it does not return of itself toward the fixed ball as in the preceding experiment; but remains at a distance from it, notwithstanding the force of torsion which tends to make it return; and it will withdraw still farther, if we present, at some distance the sealing wax to the exterior knob of the electroscope, because the influence of the sealing wax augments the quantity of resinous electricity accumulated in the fixed ball. This repulsion, under the influence of the sealing wax, is the sign by which we recognise all the cases where the tinsel and the fixed ball are both charged with resinous electricity. By proceeding in the same way with a glass tube rubbed with woollen, we should communicate to the electroscope the vitreous electricity.

65. We shall now be able to explain why it is necessary to give to the wire a length of 8 or 9 inches; such an extent facilitates the separation of the combined electricities, and the removal of one or the other with more ease; for the same reason it is useful to give nearly the same length to the metallic stem *AB* of the electroscope. But it is proper always to make it very thin, and the knob very small which terminates it, so that small quantities of electricity may, on account of the smallness of the surface have sufficient force to repel the tinsel of the movable needle, which is one of the most essential properties of the instrument.

66. The methods which we have given for communicating at
63. pleasure the vitreous or resinous electricity, are applicable to all kinds of electroscopes. All that we have said with respect to the tinsel and the fixed ball, may be said of straws or slips of leaf separated by the repulsive force. Here also it is by the influence exerted at a distance, that we develope one or the other kind of electricity; and if they are already charged, it is by the same signs that we determine the nature of the electricity which produces their divergency. But a precaution is required in this case not necessary in the electroscope of Coulomb. This is to bring the electrified body toward the knob, gradually and at first from a distance, as if we would foresee the nature of the electricity. For if the straws or leaves diverge, for example, with vitreous electricity, and we bring toward the stem of the electroscope a stick of sealing wax rubbed with woollen, besides the action of this wax to attract to it the excess of vitreous electricity spread over the stem and the straws, a decomposition of the combined electricities will also be produced; and the electricity of the same name with that of the sealing wax, that is, the resinous, will be repelled into the straws. If it should happen to be more than enough to saturate the little vitreous electricity which still remains in them, they will diverge anew but resinously; and the change from one of these repulsions to the other may be so rapid as not to be perceived. It would then seem that the original divergence was owing to a resinous electricity; which is a mistake. This will not happen if we bring the sealing wax gradually toward the knob, and we shall have time to observe the gradual weakening of the first repulsion before the developement of the second which succeeds it.

Of the different kinds of electroscopes, that of Coulomb is the most easily constructed; it is also the most sensible, and that which best preserves the electricity communicated to it. These qualities render it of the greatest utility in all delicate inquiries, of which I shall soon have occasion to exhibit some striking examples.

Of the Condenser.

67. Having presented a complete and satisfactory theory of the action of electricity, we are prepared to understand the nature of certain instruments in which it is more powerfully and more durably exhibited, either by attracting into a single point all the electricity of a system of conductors, by the influence of an electricity of a contrary nature, or by employing the permanent influence of the same quantity of electricity, to produce successively the separation of the combined electricities of several conductors presented at a distance. It will only be necessary to describe these instruments; their theory will occur of itself.

68. Where a conductor *A*, insulated and in its natural state, is placed in contact with a system of electrified conductors, or with a permanent source of electricity, it acquires a determinate charge; but if we bring toward it another body *B*, in its natural state and communicating freely with the ground, the presence of this body causes the body *A* to receive a stronger charge of electricity. In fact, the electricity with which *A* is at first covered, acts upon the combined electricities of *B*, in proportion as that body is brought nearer; it repels the electricity of the same kind into the ground, and attracts that of the opposite kind, which fixes itself upon the surface of *B* nearest to *A*. But by this same attraction, the equilibrium is disturbed in the system of conductors with which *A* communicates. A new quantity of free fluid is therefore spread over *A*, whence results a new decomposition of fluid upon *B*, and so on, till the fluid accumulated upon *A* is brought to a state of equilibrium between the repulsion which it exerts upon itself and the attraction of the fluid of *B* tending to retain it.

All these phenomena, derived directly from the theory, are completely confirmed by experiment.

We communicate to the prime conductor of an electrical machine a feeble degree of electricity, after which a metallic plate *A*
Fig. 29. being taken and held suspended and insulated by its hook *C*, by means of a glass rod *M*, this hook is made to touch the conductor. The plate thus takes a small quantity of electricity, which, when it is removed from the conductor, may cause a certain degree of divergence in the pith balls of an insulated electroscope, formed of two linen threads suspended from a stem of copper.

After this operation, the conductors will have lost so small a quantity of electricity, that they may be regarded as having very nearly the same charge as before; we touch them again in the same way, but at the same time holding, below the insulated plate *A*, another plate *B*, communicating with the common reservoir, the ground. The first plate *A* is then separated from the conductors,
Fig. 30. being still kept under the influence of *B*; in this way, it takes a charge of electricity much greater than before, as may be ascertained by presenting it anew to the electroscope. It is evident that it is necessary to withdraw *A* from the contact while under the influence of *B*; for if *B* were withdrawn first, the fluid accumulated in *A* would immediately return into the system of conductors, according to the laws of its first equilibrium.

If we repeat this experiment, holding at first the plate *B*, very distant from *A*, then a little nearer, and finally very near to it, we shall find that the charge of *A* augments more and more. This is in fact agreeable to theory; for the reciprocal attraction of *B* and *A* ought to augment in proportion as their distance diminishes; the maximum charge would therefore correspond to the case in which the distance of the two plates is absolutely nothing. But as we could not come to this limit without exciting a spark through the air which separates them, we interpose between them a body which is very thin, and very impermeable to electricity, as a plate of glass, a piece of varnished taffeta, or a thin lamina of resin. With this precaution, we may diminish the distance of the two plates, almost at pleasure. Instruments constructed in this way are called *condensers*.

69. The condenser with the glass plate is liable to be covered with moisture, which easily adheres to glass and impairs its insulating property. The condenser with taffeta cannot be compared

with itself, because the greater or less pressure of the plates upon the taffeta, causes the distance to vary, and with it the intensity of the condensation. The best method is that in which the separation is produced by a simple lamina of resinous varnish applied separately to each plate. It is only necessary to place the plates upon each other without rubbing them; for the friction would develope electricity in the lamina of resin which would adhere very strongly to its surface, and which might afterward be the cause of error in very delicate experiments. To render the use of these instruments convenient, we give to the plate *B* a solid foot of metal, and fit to the upper surface of *A* an insulating handle *M* of varnished glass. The whole apparatus is represented in figure 31. When we would make use of it, we place the plates one upon the other; we touch the lower plate *B* in order to make a communication with the ground; we next touch the electrified bodies with a knob *a* of a wire firmly attached to the upper plate *A*, which is called the *collector* plate, because it is that in fact which takes the electricity from the bodies to which it is applied. After the contact, we place the foot of the condenser upon a solid table; then, while it is firmly held there, we remove the collector plate by the insulating handle *M*, and test the electricity with which it is charged. It is necessary to separate the plates perpendicularly to their position; for if they are separated obliquely, the electricity of the collector plate would tend toward the edge of the plate nearest to *B*, and its accumulation there might produce a spark that would pierce the lamina of varnish and discharge the condenser. It is for this reason that the foot of the instrument ought to be kept firmly fixed while we remove the collector plate; for the adhesion of the two plates tends to make them slide upon each other obliquely. We must be careful, also, not to charge these instruments with a degree of electricity too great for the resistance opposed by the double insulating lamina which separates the plates; for if this resistance can be overcome, the two accumulated electricities would pierce the laminæ and unite by an explosion, as they do through the air. This is very liable to happen in the condenser with varnished plates, and for this reason, it ought to be reserved for very small quantities of electricity. When the charge is required to be strong, it is necessary to make use of the condenser with plates of

Fig. 31.

glass. But then, if the plates are not well varnished, the greater part of the accumulated electricity is spread over the glass and attached to it, so that it does not follow the collector plate when that is removed. This inconvenience may be remedied by applying to the surface of each plate, a disc of thin glass which is fixed there and which prevents the electricity from quitting this surface. But in order that very strong charges may be preserved in this way, it is necessary to prevent lateral discharges by giving to the discs a greater diameter than that of the plates, and covering the projecting portion of their surface with a thick layer of very pure varnish.*

When such a condenser communicates with an electrical machine by one of its metallic faces, the other communicating with the ground, the latter is in the same state, as if it had been brought, without a discharge, very near to a highly charged conductor. The union of these circumstances is therefore extremely well adapted to produce a strong discharge. Thus when we take in one hand the foot of the condenser, which makes us partake of its electrical state, and with the other touch the collector plate, the accumulated electricities are discharged, and unite with much force through the medium of the body. This discharge produces a shock in all the organs, which is the more violent according as the condenser is larger, its charge stronger, and its plates nearer together. This shock transmits itself through several persons holding each other by the hand, but becomes gradually weaker as it proceeds, and this diminution of force is owing doubtless to the resistance which the bodies in question, not being perfect conductors, oppose to the passage of the electric fluid.

70. The whole force of condensers may be calculated upon

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* A good varnish is very easily obtained by dissolving some sealing wax in alcohol. For this purpose, it is necessary to pulverize it and to let it remain in the alcohol for several days. The operation is quickened by warming the alcohol. When we wish to make use of this solution, we slightly warm the glass, or the substance to which we wish to apply it, and we then put it on with a brush. The alcohol is carried off by the action of the air, and the sealing wax remains. Over this may be laid a second or third coating, and so on. A more perfect insulation is effected by using gum lac in this way instead of resin.

the following principle; which indicates at the same time the manner and the limits of the accumulation which they produce. The electricity A being introduced into the collector plate, neutralizes at a distance a portion $-B$, of the contrary electricity, upon the lower plate which communicates with the ground, and prevents it from escaping. This in its turn fixes, in the same way, a portion A' of the electricity of the collector plate and takes from it its expansive force. The collector plate is therefore in exactly the same situation as if it had only $A - A'$ of free electricity; consequently it must continue to be charged until this quantity equals that which it would have taken immediately from the conductors with which it communicates, if it had been placed alone in contact with them, without the influence of the lower plate. The ratio of A to $-B$ and of $-B$ to A' depends on the greater or less distance between the plates. But, in all cases, $-B$ must be weaker than A, independently of the sign, so that if A is vitreous and B resinous, these two quantities united, will become vitreous. For the attractions of the particles $+A$ upon $-B$ must be less at a distance than it would be in contact; since, therefore, they neutralize $-B$ and take from it its expansive force through the insulating lamina, they must compensate by their number for the weakness of their action. Consequently we must always represent B as a fraction of A. To make myself understood more distinctly, suppose B $\frac{99}{100}$ of A, and see what follows from this supposition.

While $+A$ neutralizes $-B$ through the thickness of the insulating lamina, in the same way $-B$ neutralizes a portion A' of A; and the manner of action being exactly the same, the proportion neutralized must also be the same, that is, $\frac{99}{100}$. Thus A' will be $\frac{99}{100}$ of B, and as B is itself $\frac{99}{100}$ of A, it follows that A' is $\frac{99}{100} \times \frac{99}{100}$ of A or $\frac{9801}{10000}$ of A. The excess of A over A', which is the portion of electricity that remains free upon the collector plate, will therefore be $A - \frac{9801}{10000}$ of A, that is, it will be $\frac{199}{10000}$ of A; a fraction very nearly equal to $\frac{1}{50}$ of A; and thus this plate will continue to acquire electricity till the fiftieth part of its charge equals the quantity which it would naturally take from the same conductors, if it were presented to them alone and without the influence of the lower plate. Its charge, therefore, under this influence, will be fifty times greater than in the state of separation.

71. The mode of reasoning which we have now made use of, shows generally that the condensing force of the instrument depends on the fraction which expresses the ratio of saturation at a distance between its two surfaces. The nearer this fraction approaches to unity, the more nearly equal will the quantities of electricity be, which may be neutralized through the insulating lamina, and the less will be the excess of electricity which remains free upon the collector plate. The ratio of this excess to the whole charge may always be calculated, as in the preceding example, and being inverted, it will give the measure of the condensation.

It is here supposed that we know the value of the fraction which expresses the ratio of saturation at a distance between the two plates. This we determine by experiment in the following manner; we insulate the instrument and charge its collector plate with any quantity of electricity, the lower plate communicating with the ground. This being done, the communication is broken off; and the two plates having become insulated again, they are separated parallel to each other with their insulating laminæ, being held by their glass handles; we next apply the trial plane to each of them, at a point similarly situated, for example, upon their circumference, and measure by the torsion balance, the charges thus acquired. They will be proportional to the thickness of the electrical strata at the points of contact, and consequently to the total quantities of electricity of the two plates, since these are supposed equal in magnitude, and the points of contact are similarly situated. Thus the charge taken from the collector plate may represent A, and the charge taken from the lower plate $-B$; and the ratio of the latter to the former will be the ratio of saturation; whence we may deduce by calculation the measure of the condensing force. This method is more certain than to endeavor to determine directly the proportion of condensation, as it would seem that we might do, by comparing with the trial plane the charge which the collector plate receives from the same system of conductors when it is alone and when it is under the influence of the other plate. For, in order that this comparison may be exact, it is necessary that in the two cases, the conductors should be charged to exactly the same degree; and of this equality we can never be certain.

72. The condensing force being determined, the absolute effect

of the condenser depends still on the absolute quantity of electricity which the collector plate would take from the conductors by which it is charged, if it were placed alone in contact with them. But, other things being the same, this quantity must increase with the surface of the collector plate. Therefore condensers of a large diameter will accumulate more electricity than those of a smaller diameter, and must give greater shocks on being discharged; and this is in fact confirmed by experiment.

These reciprocal neutralizations which we have made use of for the purpose of calculation, may be rendered sensible by the following experiment.

73. After charging a condenser constructed with a plate of glass, the lower plate of the condenser communicating with the ground, insulate the whole apparatus, and first touch the lower plate; we shall draw from it no electricity; consequently all the electricity upon it is disguised. Then touch the upper plate, and a spark will be given; still the electricity will not all be carried off; a considerable portion will remain in a disguised state. To render it sensible, touch anew the lower plate. It will now give a spark; for its electricity is not all disguised, since we have taken away a part of that which retained it by its action at a distance. But by this contact a new portion of the latter has become free; the collector plate will therefore give another spark, and so on till the two plates are completely discharged. It is easy to determine by calculation the law of this progression from the constant ratio of saturation at the distance between the two plates. We thus find that the first contact takes away more electricity than the second; the second more than the third, and so on; and that these quantities follow a decreasing geometrical progression, having for its ratio the ratio of saturation.

When we touch both plates at once, all the electricity which would have escaped from the two faces by the successive contacts, is transmitted simultaneously through the body, and this single shock completely discharges the condenser.

74. I have said above that in the condenser with a piece of glass and naked plates, the greater part of the accumulated electricities does not adhere to the surface of the plates, but attaches itself to the opposite faces of the glass. In that case, the two

plates have properly no other effect than to establish a free communication between the different points of each of the two faces of this glass, in order that the electricity may easily spread itself over them and may also escape, at the moment of the discharge, from all their points at once. This may be easily verified by experiment; for this purpose, after having charged such a condenser, place it upon an insulator; then with the hand remove the upper plate by its insulating handle, and touch it; we shall receive from it only a small spark, and the expansive force will remain with the other plate. This being done, remove also the glass plate, lifting it by one of its edges, and touch the lower plate; this will give a spark in its turn, but also very small. It follows from this that the accumulated electricities have remained attached to the two faces of the glass plate; and in fact if we replace it between the two insulated plates of the condenser, without communicating to them, or to it, any new electricity, the condenser will be found to be recharged of itself almost as strongly as at first. Or otherwise, without replacing the glass between the two plates, if we apply both hands directly to its two faces, so as to touch a great number of points at once, we shall feel a discharge, just as if the glass had again been covered with the plate; because the extent of contact of the hands permits a large number of points of the two surfaces to discharge themselves at once. But if, instead of touching the faces of the glass with the open hands, we merely move over them the extremities of the fingers, we shall only perceive a slight sparkling and a local discharge in the points touched; no general discharge, however, will take place, and thus we shall be exposed to no violent shocks.

75. Æpinus, who was indeed the real inventor of this instrument, contrived an experiment in some respects the reverse of the the preceding, which shows very evidently what is the precise use of the insulating lamina interposed between the two plates. He employed for plates two large circular pieces of wood covered with sheets of tin; and having brought them toward each other in a parallel direction, without any thing being interposed except the stratum of air which separated them, he caused the upper plate to communicate with the conductors of an electrical machine, the lower communicating with the ground. This apparatus, it will be

perceived, is a true condenser, an aërial lamina taking the place of the varnish ; it is charged, also, in the same way as a condenser is charged, and it gives a shock when, the lower plate being touched with one hand, the upper is touched with the other. In order to obtain considerable shocks from this apparatus, it is necessary to employ large plates ; for since we are obliged to keep them at a considerable distance that sparks may not escape from them directly through the air, the extent of surface must compensate for the weakness of the condensing force. Besides, this extent seems to be one cause which retards the spark when the plates approach parallel to one another. Its effect is in a degree the reverse of the effect of points. The only difference between this and the common condenser is, that the surfaces of the insulating lamina have no real existence, except when the two plates are in presence of each other, for they are nothing else but the aërial limits of the surfaces which the two plates mutually present to each other.

76. Although Æpinus actually invented the condenser, as we have said, and gave its true theory, as may be seen in his treatise, it was Volta, who by uniting it to the electroscope, rendered it useful in discovering and making sensible the most feeble sources of electricity.

Indeed, we often meet, in physical inquiries, with sources of electricity capable of affording only very feeble repulsive forces, and which fail entirely when they have attained a certain limit ; but which, if we destroy the electricity thus produced, develope it anew. Of this we shall soon present several examples. Suppose a communication between one of these constant sources of electricity and the collector plate of the condenser whose insulating lamina is exceedingly thin, a single layer of varnish, for example. It is evident that the electricity from this source will go on accumulating in the condenser till the quantity not disguised is equal to what the collector plate would receive directly from the same source. Let us denote this quantity by E. When we have reached the limit in question, if we separate the condenser from the source of electricity, and remove the collector plate, its charge will be equal to the quantity E multiplied by the condensing force. It may therefore become sensible, however weak E may be, if the ratio of saturation differ little from unity, that is, if the distance

between the plates of the condenser is very small, a condition which the layer of varnish perfectly fulfils.

In order to unite the indications of this instrument with those of the straw electroscope, which Volta commonly used as being the
Fig. 32. most portable and the most convenient, we unscrew the upper knob from the stem, and substitute in the place of it, the lower plate of the condenser. This plate is then insulated by the glass case of the electroscope. It is made to communicate directly by a metallic wire with the constant source of electricity, and we merely touch the upper plate to make it communicate with the ground. With this arrangement, it is the lower plate which collects the electricity. When we think the charge sufficient, we separate it from the constant source without touching it, keeping for that purpose an insulating rod; we then remove the upper plate by its insulating handle. The electricity of the lower plate, becoming free, manifests its repulsive force by the divergence of the straws. It is then easy to determine its nature by the usual tests. It is sometimes more convenient to make the constant source communicate with the upper plate of the condenser; we then touch that which communicates with the straws. When the instrument is charged, we cease to touch it; it is separated from the source of the electricity, and the upper plate is removed which carries away with it the electricity which it had acquired. Then the lower plate which is left insulated, preserves the contrary electricity and manifests it by the divergence of the straws. Its charge is, in this way, somewhat less than that of the collector plate, in the first method, since the ratio of saturation at a distance is always fractional. But the difference will not be sensible, if, as we suppose, the lamina is very thin, because this ratio will then approach exceedingly near to unity. It is only necessary to remember that this electricity is of a different nature from that of the source.

It is evident that we might equally well apply the condenser to the electroscope of Coulomb; but as the method is exactly the same, it is unnecessary to describe it here.

Of the Electrophorus.

77. When a body is electrified and insulated, if we bring toward it another body not insulated, the latter will take the contrary electricity, and if it be suddenly insulated, it will be free to be charged with this electricity. This has been shown several times in the preceding sections, and may be proved again in different ways.

We charge the conductors of the machine with a certain quantity of eleotricity, and bring toward them at a distance, a metallic disc supported by a glass rod. If we withdraw this disc without having touched it, it will be found to be in its natural state; but if we touch it while within the influence of the conductors, and then remove it, first taking off the hand, we shall find it charged with electricity the opposite to that of the conductors.

We take a metallic disc supported upon a stand, insulate it and give it a spark; after which we use it as in the preceding experiment, to charge another metallic disc, by touching it and then insulating it. This phenomenon is renewed until the electricity of the insulated disc has been entirely lost by the contact of the air.

78. In order to know what takes place with respect to the electricity of this disc, while it is thus acting by influence, we have only to make the lower surface of the disc communicate with an electroscope consisting of threads, insulated like the disc; the threads instantly diverge. But as the uninsulated disc approaches, their divergence diminishes; it finally becomes to appearance nothing, and the electricity seems to be destroyed. But it is in fact only disguised; for when the disc which communicates with the ground is withdrawn, the threads begin to diverge anew as strongly as at first.

The decomposition of the natural electricities of the presented body, and consequently the quantity of electricity with which it becomes charged, augments according as its distance from the electrified body diminishes, and it would be at the highest degree of intensity if this distance were nothing. But we cannot diminish it indefinitely without exciting a spark between the two bodies. It is

for this reason that we interpose between them a thin plate formed of some substance impervious to electricity, as a plate of glass or a layer of resin.

In order to show the application of this method, we insulate a metallic disc, the lower plate of a condenser, for instance; we protect it with a plate of glass and give it a spark. Upon this plate we place the other plate of the condenser which is provided with an insulating handle; we touch its upper surface for an instant; we afterward remove it by its handle and find it charged with electricity the opposite to that of the insulated disc. This experiment may be repeated as many times as we please; and for this reason the instrument has received the name of *electrophorus*, that is, a bearer of electricity.

79. We perceive that the condenser and the electrophorus are both founded upon the electrical action exerted at a distance. But in the condenser, we make use of the presence of another body communicating with the ground to augment the charge of an insulated body, while in the electrophorus it is the insulated and electrified body by which the accumulation is produced.

An electrophorus may be constructed in which the thickness of the insulating lamina shall be altogether insensible. For this purpose, we have only to employ for the lower disc a plate of glass or a layer of resin electrified by friction. These substances strongly retaining the electricity, we place the upper disc immediately upon the surface, without their imparting to it any considerable quantity of the fluid; while the influence, exerted in decomposing the natural electricities of this disc, will be very great. The most common
Fig. 33. electrophorus is constructed in this way with a cake of resin run into a metallic dish. We electrify the surface of this cake by rubbing it with a dry cat skin. It takes the resinous electricity, and its influence causes in the upper plate the vitreous electricity. This apparatus is of use in chemical inquiries in which we have frequent occasion for electricity.

80. When the apparatus is charged and placed upon the resin, the vitreous electricity which resides upon its lower surface, and the contrary electricity developed upon the resin, mutually neutralize each other, and neither has a tendency to escape. Consequently, they cannot be dissipated by the contact of the air, which could

hardly insinuate itself between the surfaces where they reside. An instrument thus charged ought to preserve for a long time its two electricities, and they are found indeed to continue whole months if the electrophorus is kept in a dry place.

Nevertheless the permanent attraction of the two opposite electricities must gradually overcome the resistance which the resin opposes to the disengagement of its own resinous electricity, and to the introduction of the vitreous electricity of the plate. This is probably the only cause why, after a longer or shorter time, the electrophorus is finally found to be discharged, and its different parts reduced to their natural state.

The effects of this reciprocal attraction may be accelerated by greatly increasing its energy. For this purpose, when the electrophorus is charged, remove the metallic plate and place it anew upon the resin, not parallel to its plane and in the direction of its surface, but obliquely and with the circumference toward the resin. Then its vitreous electricity accumulating almost entirely in the part of its circumference which touches the resin, will take a much greater repulsive force. It will leave the plate, completely neutralize the points toward which it is directed, and after several contacts in different parts, the cake of resin, will be found to be entirely discharged.

81. We hence derive a curious experiment. Instead of restoring to the resin the vitreous electricity developed by its influence in the metallic plate, apply it to another cake of resin which is in its natural state; it will, in like manner, attach itself to the surface of this plate, which will thus be electrified vitreously, and will thus become capable in its turn of developing by its influence the resinous electricity. When the second cake has been charged in this way, place a metallic plate upon its surface; we shall have an electrophorus affording an electricity the opposite to the first. We can make use of this in the same way to charge the surface of a thin cake with resinous electricity; and this series may be extended to any number of cakes which will be electrified alternately with vitreous and resinous electricity.

82. By this process we can electrify also the surface of each cake only in certain determinate parts. For this purpose, it is sufficient to adapt to the disc which conveys the electricity a stem

and a metallic knob like those of the collector plate of the condenser. Then if we touch the resin with this knob, the electricity will flow entirely to the point of contact. By taking a succession of points, we can trace the outline of a proposed figure.

If we would render these points visible, we have only to sprinkle over the surface of the resin some light non-conducting powder, as the dust of resin or sulphur. The small particles of dust attach themselves only to the electrified parts, so that by inverting the cake, all those not thus retained fall off by their own weight, and the electrified lines remain covered with these particles. We observe that the particles of dust take regular but different arrangements according to the nature of the electricity by which they are retained; and hence by forming lines with the two electricities upon different parts of the same cake, we obtain at the same time two sorts of figures. This curious experiment was first performed by Lichtenberg, a German philosopher, and the figures thus traced are called Lichtenberg's figures.

To render this phenomenon more apparent, we make use of a mixture of sulphur and red lead rubbed together in a mortar. The friction thus produced electrifies the sulphur vitreously and the red lead resinously. We put this powder into a kind of bellows which serves to throw it over the cake of electrified resin. Then the two substances, attaching to the cake, become separate and distinct both by their arrangement and their color; the sulphur being yellow and the lead red.

Soon after this discovery, some German philosophers remarked that the powder of resin, thus spread over an electrified cake, exhibited very slight progressive motions, which appeared however not to have any regularity. Upon this, a theory was soon formed; but more attentive observers discovered that these motions were produced by a little insect, called *acarus*, which is often found in the powder of resin.

Of the Leyden Jar.

83. In the preceding articles, we have examined the phenomena which are produced by the vitreous and resinous electricities,

when disguised by each other in virtue of their action at a distance. We have seen that when they are in this state, if we present to them conducting bodies which communicate from one to the other, they dart with force upon these conductors, unite, and thus return to their natural state of combination.

The experiments which we are about to perform relate to the same kind of action, and are to be explained on precisely the same principles; but they are worthy of particular attention because they furnish powerful means of accumulating the electric force, and because they give rise to numerous phenomena which require this accumulation.

We take a glass vessel, as a tumbler, for example, partly filled with water, and holding it in the hand, we introduce into the water a wire or other conductor communicating with the prime conductor of an electrical machine. After a few turns of the plate or cylinder, if we attempt to remove the conductor with one hand, holding the vessel always in the other, we shall receive a shock which will be the more violent according as the vessel is larger, the machine more powerful, and continued in action for a longer time.

84. This experiment, which was performed long before the invention of the condenser and the electrophorus, and before electricity was reduced to a theory, was the result of accident, but of an accident that excited attention. It first presented itself at Leyden to Cuneus and Muschenbroeck. The phenomenon was to them an occasion of surprise and even of terror. It was repeated every where, and being soon familiarized with the particulars which had at first excited so much apprehension, philosophers attempted to discover the arrangement best fitted to produce an effect so wonderful. They first discovered the necessity of a conducting substance, as water, mercury, or sheets of metal applied to the inner surface of the vessel; they soon perceived also the importance of an exterior coating of a conducting nature, as the hand performed this office in a very imperfect manner. Finally they discovered that it was indispensable to cut off all communication between the inside and outside of the vessel, or rather between the inside and outside coatings, except at the instant of the explosion.

These conditions are fulfilled in the best manner by taking a phial or jar of common flint glass, and pasting or glueing upon the

outside a thin sheet of metal, as tin foil, the inside being coated in the same manner, or filled with leaves of metal. A metallic rod terminated without by a ball, passes through the stopper of the jar and serves to convey the electricity to the interior. The stopper and a part of the neck are usually varnished on the outside. This instrument, which is represented in figure 34, is generally called the *Leyden jar*, from the name of the city where its properties were first observed.

85. The theory of the instrument agrees so exactly with that of the condenser, that almost the same language may be used with respect to both.

The electricity which is introduced within the jar, and which we will suppose to be of the vitreous kind, decomposes by its influence the natural electricities of the outer surface, drives off the vitreous, fixes the resinous, and by the reciprocal attraction of the resinous is itself partly fixed in turn; and thus the jar forms a true condenser. When a communication is made by the hand or by both hands between its two faces, the two electricities accumulated there rush toward each other with great rapidity, and traversing the bodily organs produce in them a violent shock; or, which is the same thing, the body which is the medium of communication suffers a rapid decomposition of its natural electricities, each of which tends to that surface of the jar where the opposite electricity resides.

This explanation may be verified in every particular by experiments similar to those employed in the case of the condenser. Generally, the Leyden jar is simply a condenser, in which the insulating layer is curved, and which has for its coating or armor, as it is sometimes called, on the outside, the sheet of metal with which the jar is covered, and within, the conducting substance with which the jar is filled or covered.

86. When an electrified Leyden jar is suspended in the air, the absorbing action of that fluid can act only on the portion of electricity which is free upon either surface of the glass, and the reciprocal action of the two disguised electricities serves to protect them both. This is very evident from the long time which Leyden jars of thin glass take to discharge themselves completely, when they are insulated and when the direct communication of their two surfaces is interrupted by a layer of pure gum lac.

If we examine, at different times, the progress of this absorption, by touching the two surfaces with the trial plane, we shall find that there have been developed upon each quantities of free electricity, of a contrary nature, which finally become sensibly equal; after which they maintain themselves in this state of equality until both are completely exhausted. We are able, by means of the calculus, to account very exactly for this phenomenon, according to the laws of the absorption of electricity by the air. When, however, the equality of the charges is thus established upon the two surfaces, if we spread upon each a non-conducting powder, it would evidently adhere by the attraction of the free electricity; and if, moreover, the electricity were not strong enough to repel the particles, they would thus be preserved from the contact of the air; and thus, there being no waste, the jar will remain charged for an indefinite time. This we in fact observe, when the two surfaces of a thin glass jar, after being charged, are covered with a mixture of sulphur and red lead, of which we have spoken above. If we suspend such a jar by a cord along a dry wall, it will preserve its electricity for months.

87. When we are employed in electrical experiments, we ought never to lose sight of the influence derived from the contact of the air. Overlooking this, we are apt to believe, for instance, that a Leyden jar, or other instrument of the kind, may be charged merely by receiving the electricity of the machine upon one of its faces, without communicating by the other with the ground; for, indeed, a jar thus insulated is gradually charged especially if it is electrified for a long time. But this is because the electricity of its other surface, repelled and rendered free by influence at a distance, is exposed to the absorbing action of the air which slowly diminishes it, and thus permits the accumulation of a certain quantity of electricity upon the surface communicating directly with the machine. To make this effect conspicuous, we have only to arm the outer surface with several points; the jar, although insulated in the air, is charged almost as strongly as if the surface armed with points had communicated directly with the ground.

Of the Electric Battery.

88. When we wish to accumulate a large quantity of electricity, we form several Leyden jars of a large size, coating the two surfaces with tin foil, and connecting the interior surfaces together, and the exterior together, so that when they are charged by communicating with the conductor of an electrical machine, they may all be discharged at the same time. This apparatus is called an electric battery; it is represented in figure 35. It is usually placed upon an insulating support, which communicates with a metallic conductor that may be removed and replaced at pleasure.

The greater the extent of armed surface a battery contains, the more electricity it accumulates, the action of the machine being the same; it requires also more time to charge it. Generally, when we make use of large batteries, it is useful to separate them into several parcels in order to be able to proportion the quantity of electricity to the effects to be produced. By this means we are able also to charge batteries more rapidly with the same machine.

89. Suppose any number of Leyden jars, or armed surfaces of glass, suspended under each other by metallic conductors, as represented in figure 36. We attach the first to a cord of silk S, and make the last communicate with the ground. We then convey upon the upper face A_1, the electricity of the machine which we suppose vitreous; it is evident that all the lower plates will be charged at the same time with the first, by the successive repulsions of the electricity of one into the other. But both reasoning and experiment show, that in this way of charging *by cascade*, as it is called, the decomposition of the natural electricities is weakened very fast, as we recede from the prime conductor; so that if we take only a small number of plates, the last are scarcely charged at all. Moreover, if we make the first and last links of the chain communicate with each other by their opposite faces, we obtain the discharge of the quantities of electricity only which they have individually acquired; and those of the intermediate plates recombine of themselves without producing any effect; whereas we may avail ourselves of their power also, if, after having charged the sys-

tem by cascade, we separate its successive parts in order to make the faces charged with the same electricity communicate with each other, and then discharge them simultaneously. The same method may be advantageously employed in charging large batteries. For this end, it is necessary to separate them into several parcels, and to place them upon insulating feet, as represented in figure 37. If we wish to charge them all or only a part of them, we at first establish a communication between the successive faces B_1, A_2; B_2, A_3; . . . . by means of the metallic rods C_1, C_2, ... which pass through rings provided for this purpose; and we make the last face B_n communicate with the ground. Afterward, when the charge is supposed to be sufficient, we destroy the communication of the face B_n with the ground. We may then safely remove, one after the other, the metal rods C_1, C_2 . . ; for when we remove C_1, for instance, no discharge can take place, for the electricity B_1 is entirely retained by A_1, and the electricity A_2 almost entirely by B_2. Nevertheless, we shall thus receive a feeble spark arising from the excess of A_2 over B_2. This being done, and the partial batteries being thus separated, we establish communications between their surfaces A_1, A_2, . . . by throwing on the same metal rods C_1, C_2, . . . (if we lay them on, we should be exposed to a discharge;) these rods meeting the conductors by which the parts of each battery are connected, naturally place them in communication. Each time the rod falls upon two consecutive parts, it excites a spark between them which comes from the inequality of the charges acquired during the first arrangement. When the batteries are all united, we can discharge them all at a single contact, by making the communication between the extreme faces A_1 and B_n; or, if we please, we can first charge them completely by a renewed motion of the machine.

In these operations, it is important to have an electrometer, or, as it is sometimes called, a *regulator* to point out at each instant the state of the battery. For, at a certain point of intensity, the portion of electricity of the faces A may have a repulsive force sufficient to overcome the resistance of the air, and by rushing with an explosion toward a face B, the battery would be discharged, and some of the jars perhaps broken, because all the force of the shock tends then toward a single point of the coating. To avoid an acci-

dent of this kind, we screw upon the conductors communicating with the faces A, a small pendulum having a metallic rod TT, and a small rod of ivory carrying upon its extremity a small ball b of elder
Fig. 38. pith. The free fluid of the faces A, exerting its repulsive force upon this pendulum, repels it from the stem; and its divergences are measured by a graduated arc traced upon the semicircle cc. It is evident that this instrument gives no absolute measure of the electricity accumulated; but affords at least a constant indication by which we can be guided, when we have de ermined by experiment, once for all, the degree of repulsion at whioh a spontaneous discharge is to be apprehended.

In discharging batteries, we make use of the exciter or discharger already described. We connect one extremity or knob with a face A, and the other with a face B, and the discharge takes place through this conductor. When we have occasion to use large batteries, care should be taken how we expose ourselves, by becoming a part of the circuit; for a discharge through the body might be attended with serious consequences.

Of the Electric Pile and of the Phenomena presented by Crystals capable of being electrified by Heat.

90. While on the subject of charging by cascade, I shall present some results which will be found useful hereafter when we come to treat of galvanism and magnetism. They will also afford some new examples of the action of disguised electricity.

Fig. 39. Imagine a series of glass plates, having the two surfaces coated with metal, and arranged parallel to each other in such a way that the face B_1 of the first shall communicate by a wire with the face A_2 of the second; the face B_2 of the second with the face A_3 of the third; and so on to the last, the lower face B_n of this last communicating with the ground. Let us suppose that, the whole apparatus being insulated, we make the first face A_1 communicate with the prime conductor of a powerful machine, and that after having thus electrified it by cascade for some time, we interrupt the communication with the conductor and with the ground by means of non-conducting rods. It is proposed to find what will be, after a

certain interval, the electrical state of the different parts of the apparatus.

To determine this, it is necessary to consider that at the moment when the communication is broken, the first face *A* contains a certain electrical charge, in part free, and in part disguised by the electricity of a contrary nature which it has itself attracted and fixed upon the second face B_1; it is the same with the faces A_2 and B_2, with A_3 and B_3, and so on through all the others. Of all these quantities there is only the charge A_1 which is foreign to the apparatus; all the others being derived from the simple decomposition of the natural electricities. The absolute intensity of decomposition varies from one plate to another; but all which is excited upon each is not sensible; there is nothing sensible except the portions of free electricity, which are all of the same nature with that belonging to A_1.

Now if the apparatus in this state were exposed in a perfectly non-conducting medium, it is evident that this state of equilibrium would continue without change; but if it were surrounded by an absorbing medium, as the air, it would gradually lose its electricity. To understand how this would take place, we must remember that in the same state of the air, and for a surface of the same form, the waste is proportional to the whole quantity of free electricity which resides upon it. Thus, in the first instants, the loss will be greater for the first face A_1 than for the second A_2, because the latter has less free electricity; so also it will be greater for A_2 than for A_3, and so on to the last face B_n, where it will be nothing, because upon this face there is no free electricity. But by this series of unequal losses, free electricity will be developed. For the equilibrium before established did not exist between the portions of free electricity of the different faces, but between their absolute charges; and since the first charge A_1 is weakened, it can no longer neutralize upon B_1 all which it neutralized before; it is the same with respect to the action of A_2 upon B_2, and so on to the face B_n. The electricity of this face being no longer completely neutralized, a portion becomes free, and this portion, at first very small, gradually augments. For although, from the instant that it first appears, it is continually exposed to the absorbing action of the air, yet from its weakness, it loses at first less than the free portions of the other

faces; hence the change of equilibrium goes on gradually in the same way, the loss of free electricity diminishing more and more upon the first face and increasing upon the last, and upon the intermediate faces, varying between these two extremes. No limit can be assigned, therefore, to these variations, except it be the equality of the quantities of free electricity residing upon the two extreme faces of the apparatus, which will also reduce their charges to an equality. Then the disposition of the electricity will generally be symmetrical, as we proceed from these two faces toward the centre of the pile; the quantities of free electricity will be of a contrary nature on each side of this centre, gradually decreasing as we approach it; and at the centre they will be nothing, and we may touch the plate which is placed there without experiencing any shock. But if we break the pile at this place, or at any other, and insulate the parts, there will gradually be developed at the broken extremity, a certain quantity of free electricity, which will be of a contrary nature to that of the other extremity which was left untouched.

This result is agreeable to theory, and, as I have satisfied myself, is perfectly confirmed by actual experiment.

90. The phenomena which are presented by minerals capable of being electrified by heat, are analogous to those we have described; and we can scarcely doubt that nature has provided them with a similar apparatus, that is, with an electric pile composed of an infinite number of parallel plates. The mere detail of the facts will be sufficient to establish this truth.

I shall take as an example the variety of the tourmaline denominated by M. Haüy *isogone;* it has the form of a prism with nine faces, terminated at one end by a summit of three faces, and at the other by a summit of six faces. When this stone is exposed to a temperature less than 98° of Fahrenheit, it offers no signs of electricity; but if we immerse it for some minutes in boiling water, and then, holding it with a pair of small pincers applied to the middle of the prism, we present it to the disc of an electroscope or to the small pendulum, already charged with a known electricity, we shall see that it is attracted by one end and repelled by the other. The summit with three faces possesses the resinous electricity, and the summit with six faces the vitreous. By making the electroscope

very sensible, we find that each kind of electricity goes on decreasing rapidly from the summit where it resides; that it becomes very feeble at a small distance from each extremity of the prism; and that from this point to the centre, the mineral appears to be in its natural state; in a word, the effects are absolutely the same as in the insulated electric pile described above.

Many other crystals have since been found to exhibit similar phenomena. Several are more sensible in this way than the tourmaline, a small increase of heat being sufficient to electrify them. M. Haüy, who has made many curious researches on this subject, has remarked that the property in question belongs only to crystals whose forms are not symmetrical, and that the parts where the opposite electric poles reside, vary always from symmetry, as the two extremities of the prism of the tourmaline.

It is possible that a very great depression of temperature in the case of the tourmaline might destroy its electrical equilibrium, as an elevation of temperature is known to do, or that it might be destroyed by a less degree of heat, if the stone were previously exposed to extreme cold. These particulars, which might serve to clear up the mystery of the electrification of this mineral, deserve to be examined.

When melted sulphur is poured into an iron basin, and suffered to cool in this basin while insulated, we find that it acquires the resinous electricity, and the iron the vitreous. This fact seems to indicate what takes place in each element of the tourmaline and of the other crystals which are electrified by heat. A series of such elements, being placed in contact with each other, would probably form a true electric pile, in which the insulation and separation of the plates would be effected by the non-conductibility of the substance of the crystal.

Mechanical and Chemical Effects produced by the Repulsive Force of accumulated Electricities.

91. We have already remarked more than once, that the electricity spread over the surface of conducting bodies, exerts a contrary pressure upon the atmosphere which retains it at this surface

by its weight. We have seen that this reaction, which is always proportional to the square of the thickness of the electric stratum, may become sufficiently powerful to overcome the resistance opposed by the air. Then the electricity escapes through the particles of the air. Hence we infer, that at higher degrees of accumulation, the electricity becomes capable of breaking through substances much more dense than the air, and even of separating their particles. This is confirmed by experiment.

The force of an electric battery, when highly charged, is sufficient to break cylinders of wood through which it is made to pass. It inflames certain combustible bodies, as phosphorus, ether, and other spirits, that is, it causes them to combine with the oxygen of the air, especially if they have been previously warmed. It destroys life when it is made to pass through the body of an animal, and the flesh soon putrefies like that of animals killed by lightning. It passes also through plates of glass lengthwise and breaks them, provided their surfaces are polished; for otherwise the glass would be a conductor and the discharge might pass without breaking it. If transmitted along a fine wire of iron, silver, or copper, it melts it into little globules. With a degree of accumulation still more intense, these wires and even thin leaves of metal are suddenly volatilized.

It is evident that such a force might, by a similar action, produce in liquid or gaseous substances, all the phenomena which result naturally from a strong compression or from a sudden elevation of temperature; and this is in fact observed to take place. Thus the electric discharge, even that of a simple Leyden jar, inflames hydrogen and oxygen when they are mixed together in the proportion of about two parts by bulk of hydrogen to one of oxygen; and the residuum is water, or rather the vapor of water, elevated to a high temperature by the great quantity of caloric which the combination disengages. The most convenient apparatus for this experiment is represented in figure 40. It consists of a large glass globe, kept filled with oxygen gas by making it communicate with receivers having a constant pressure. Into this globe issues a constant current of hydrogen gas through a very fine glass tube. The jet is inflamed by a feeble spark sent through the globe by metallic conductors, and the combustion having once begun, supports itself.

This experiment requires much caution to avoid explosions; but when we wish to observe only the fact of the combination of the two gases, we can safely employ the apparatus represented in figure 41. This is a glass tube closed at top with a metal stopper, which is strongly luted and which has a small knob projecting without the tube. A flexible metallic rod rises in the same tube by a spring, and approaches within a small distance of the knob. Then the tube being immersed in a trough of water, is filled with gas like a common receiver; and being drawn partly out and wiped, a spark is given to the metallic cap; it passes through the gaseous mixture, and causes inflammation with a loud noise. The same effect is produced by simple mechanical pressure; and also by an elevation of temperature.

In the same way that we form water by the electric spark, we are able also to decompose it. To this end, recourse was had formerly to violent discharges through the liquid, which produced in it explosions accompanied with sparks. But the able and ingenious Dr. Wollaston contrived to produce the same effect in a much more certain, easy, and beautiful manner, by conducting the electric current through the water by means of very fine platina wires, terminating in sharp points, and insulated in glass tubes, or enveloped in resin, that they might not lose their electricity, except at the points themselves. It is evident that a very feeble electricity will, under these circumstances, acquire an extreme intensity, which is confined to the extremity of the point, and acts entirely against the single particle of water with which the point is in contact. Thus the electric current of a feeble machine, being transmitted in this way, is sufficient to disengage a continued stream of little bubbles, which being collected and tried by the electric spark, are found to be the two gases of which water is composed. The effect is rendered more certain and rapid by bringing together at the same time, through two opposite wires, two currents of electricity of different kinds.

If the transmission is made by two very fine points, one of copper, and the other of silver, immersed in a solution of sulphate of copper, the first communicating with the vitreous conductor, the sulphate is decomposed. The copper, being separated from the acid, is deposited in a metallic state, upon the silver wire, and the

other wire is dissolved. If we invert the communications, so as to cause the silver wire, thus covered, to communicate with the vitreous conductor, the deposit of copper, formed upon its surface, is redissolved, and the precipitation takes place upon the other wire.

These beautiful experiments, and many others of the same kind, due also to Dr. Wollaston, prove that the resinous electricity tends to disengage oxygen from the combinations into which it enters, and that the vitreous electricity, on the contrary, favors these combinations. Of the truth of this important result we shall hereafter have abundant proof.

Of Atmospherical Electricity and Lightning Rods.

92. Since the discovery of the Leyden jar and electrical batteries, the effects of the electricity accumulated in this way, are found to be so similar to those of lightning, that the identity soon began to be suspected. Yet Franklin was the first, who, having observed the power of points to discharge electrified bodies at a distance, thought of employing this method of rendering atmospherical electricity sensible, and of securing us from its effects. But not having in America the means of making these experiments, he engaged the philosophers of Europe to attempt them. The first who answered to this suggestion was Dalibard, a French philosopher, who built a hut at Marly-la-ville, upon which was erected a bar of iron forty feet in length, insulated at its lower extremity. A stormy cloud passing near the zenith of this bar, it gave sparks when the finger was presented to it, and exhibited all the effects of conductors electrified by our common machines. This memorable experiment was performed for the first time on the 10th of May, 1752.

Contrivances of this sort were soon multiplied; but they all had a common defect, namely, the imperfect insulation of the base, which was liable to become wet and thus suffered the electricity to be dissipated. Canton remedied this imperfection by placing at the lower extremity of the metallic bar, a metal cap which covered the nonconducting support and protected it from the rain. By means of this improved apparatus, he found that certain clouds are charged with vitreous electricity, others with resinous; so that the

electricity of the apparatus often changed five or six times in half an hour. Rain and snow in falling electrified it also, and this took place in winter as well as in summer. That he might not be obliged to visit it continually and often without success, Canton fitted to it a small and extremely ingenious apparatus. It is composed of three little bells T, T_1, T_2, suspended from the same metallic horizontal rod AB; the middle one T by a thread of silk, and the two others by a metallic chain. Moreover, the bell T communicates with the ground by another chain attached to its under surface. Between these bells two metallic balls b, b', are suspended by silk threads. Now it is evident that if the rod AB is made to communicate with the vertical conductor which receives the electricity of the atmosphere, this electricity will first be transmitted to the two extreme bells T_1, T_2, by means of the metallic chains to which they are suspended. Then the little balls b, b', will be attracted toward the bells and will touch them; but they will be immediately repelled, and on the other hand, they will be attracted by the bell T which communicates with the ground; they will touch this bell, be discharged, and return to receive a new charge from the extreme bells. These continued oscillations of the little balls will produce a ringing of the bells, and we shall thus be apprised of the presence of electricity. This apparatus is called the *electrical chime*. Fig. 42.

93. But Franklin had been pursuing in America, the train of thought which first suggested itself to him, and in which he felt a strong interest. In the want of high buildings, it occurred to him that the electricity might be made to descend from the clouds to the earth along the cord of a boy's kite; and since the beautiful experiments of Newton upon the colors exhibited by soap bubbles, this was the second time that the sports of children became the instruments of the most important discoveries. But Franklin did not foresee the extreme danger to which we was exposing himself. His kite was raised, and he held the cord in his hand; but it gave no sign of electricity although it was near a cloud which appeared to be charged with lightning. Franklin began to fear that he was wrong in his conjectures, when, a small shower having moistened the cord and increased its conducting power, he drew sparks from it; and he himself describes the joy with which he perceived the phenomenon he had thus anticipated. Nevertheless, if the cord

had been thoroughly wet, or if it had been a better conductor, it is highly probable that this celebrated man would have paid for his temerity with his life; and we should have been deprived of all he afterward achieved for science, philosophy and liberty. In France, M. de Romas performed the same experiment in a much more perfect manner, having either conceived it himself, or having been led to it by the attempt of Franklin. He twisted a very fine iron wire with the cord of the kite, and that the observer might not be exposed to sudden discharges, the lower extremity of the cord was terminated by a silk string eight or ten feet in length, by which the kite and wire were insulated. Moreover, instead of taking sparks with the finger, when the observer himself receives the discharge, Romas obtained them by means of a metallic conductor communicating with the ground, and held in the hand by a non-conducting
58. tube; this was in fact the exciter already described. Having thus given to his apparatus all the perfection which skill and prudence suggested, Romas did not hesitate to send it into the most highly charged clouds; and in one of his experiments, during a storm which was not remarkable either for the quantity of lightning or of rain, he saw shoot from it for some hours jets of fire more than ten feet in length. "Imagine to yourself," says he to Nollet, "sheets of fire nine or ten feet in length and an inch in thickness, accompanied with an explosion louder than the report of a pistol. In less than an hour I obtained certainly thirty of this size, besides a great number of smaller dimensions. But what gave me the most pleasure was, that the large sheets were spontaneous, and that in spite of the great quantity of fire that composed them, they fell constantly upon the nearest conducting body. This constancy gave me so much confidence that I did not fear to discharge the fire with my exciter, even when the storm was the most violent; and although the glass branches of the instrument were only two feet in length, I conducted at pleasure, without feeling the smallest shock in my hand, sheets of fire, six or seven feet in length.' This description is alone sufficient to show that such experiments are not to be tried without extreme care. There is one precaution which I cannot omit giving, because it is of the greatest importance, and because it applies equally to insulated metallic rods, elevated after the manner of Canton; this is, to place near the lower extremity

of the bar or of the cord of the electric kite, a large iron bar inserted to a considerable depth in the earth or communicating with a body of water. When the current of electricity becomes strong enough to be dangerous, the explosions will take place upon the projecting extremity of the bar rather than upon any other object more distant or even equally removed; and by taking this precaution, we may enjoy the spectacle without danger.

It being once established that the lightning is an electric explosion, we cannot doubt that the electricity of a thunder cloud, like that of our machines, may be considerably weakened by the action of points. This inference did not escape the notice of Franklin; for among the distinguished features of his genius, was a readiness to seize upon any useful application of new facts, no less remarkable than his aptitude to discover them. When he had no longer any doubt respecting the nature of lightning, it immediately occurred to him to neutralize it by the power which he had discovered in metallic points, and thus he was led to the invention of the *lightning rod*.

94. This name is given to those metallic rods, which are raised upon the tops of buildings, the masts of ships, &c. One of the extremities, which is pointed, projects into the atmosphere, while the other communicates with the ground. The effect of this apparatus is to receive or neutralize the electricity of the clouds, and to conduct it without an explosion into the earth. For about fifty years, during which they have been in use, their utility has been proved in a great number of instances; indeed their effect is evident from theory. When an electric cloud passes so near as to make its influence sensible, it decomposes the natural electricities of the rod, repels that of the same kind into the ground, and attracts that of the opposite kind to the upper extremity, where it acquires an intensity depending upon the action of the cloud. Hence it results that the particles of moist air situated between the cloud and the lightning rod, must be attracted toward the point with great rapidity, lose there the electricity which they had received from the cloud, and be violently repelled charged with the contrary electricity. Then flying toward the cloud, they neutralize the electricity of such of its particles as they meet with in their passage, until by this alternate motion, the cloud is completely discharged. There

is hence reason for believing that this discharge will take place without explosion, and that all conducting bodies below the lightning rod and at a small distance from it will be thus preserved. If, however, in an extraordinary case, this rapid discharge of the electricity should not be sufficient, and an explosion take place, it will infallibly strike upon the point, because there the reciprocal attraction of the two opposite electricities is incomparably the most powerful, and in this the theory is fully confirmed by the fact. Soon after the invention came into use, the point of a lightning rod was presented to the Academy of Sciences at Paris, which had received so powerful a discharge that it had been melted, as fine wire is melted by our batteries. Yet this terrible explosion, which would naturally have been attended with the most destructive effects to the house upon which it fell, did not cause the slightest injury, and was perceived only by the loud thunder which accompanied it.

We are able by a very simple experiment to show the effect of lightning rods upon a charged cloud. We suspend from the conductor of an electrical machine a linen thread, to the lower end of which is attached a lock of carded cotton which very well represents a cloud. The whole is electrified, and we present to the cotton, not a point, but a spherical body communicating with the ground; the cotton is immediately attracted, and a spark is produced between the two bodies. But if, instead of a sphere, we present to the cotton a point communicating with the ground, held at a great distance, it discharges itself insensibly after which it returns toward the conductor to be recharged, and redescends toward the point to discharge itself anew. We can suspend in this way several locks of cotton by threads of different lengths, and they will be seen to fold successively upon each other. It is thus, probably, that the lower portions of a cloud, which have been discharged by a lightning rod, fold upon the upper parts which are still electrified.

95. The effect and utility of lightning rods being no longer doubtful, it is important to know the best method of constructing them. Two conditions seem to be indispensably necessary; the first is, that the communication should be perfect with the ground and between the different metallic bars of which the apparatus is composed; the other is, that the conducting rods should be of such

a magnitude that in the most violent explosions, the electricity transmitted shall not acquire a repulsive force sufficient to make it fly off. It appears from all the instances hitherto observed, that rods of an inch square, or an assemblage of large iron wires of equivalent dimensions, are perfectly sufficient for this purpose.

If these conditions are strictly observed, theory as well as experiment tends to show that there is no danger from being in the vicinity of a lightning rod or even from being in contact with it, the electric charge always choosing the best conductors, and consequently following the metallic rods rather than any neighboring body of less conducting power. Thus, when an iron wire is made to pass through a package of gunpowder, we may safely transmit, by means of this wire, any electric discharge which is not sufficient to melt it, or to heat it to such a degree as to inflame the powder. Also, let a bird stand on one of the conductors of the machine, during the discharge of a battery, it will not be affected, although the course of the electricity comes in contact with it. Finally, by surrounding the body with a metallic wire, the extremities of which are held in the hand, we may safely discharge the largest batteries through this wire, if, like the bird, we are insulated on the line of communication.

In these experiments we sometimes feel a slight, instantaneous shock, but incomparably weaker than that produced by the discharge of the battery. The cause of this shock is, that the electricity accumulated in the battery is not transmitted with perfect freedom, and is not discharged in a single indivisible instant, however good the conductor which is presented to it. In this case, it acts by influence upon the natural electricities of the bodies in contact with this conductor, and produces in them a separation which continues for an instant. The equilibrium is immediately restored, but the sudden alteration of these two states produces a slight disturbance in the bodily organs. From this it will be seen that the effect will be the more feeble according as the communication between the two surfaces of the battery is effected with larger and more perfect conductors.

To show the truth of these remarks, we insulate a cylindrical conductor *AB*, and place it in contact with the exterior surface of a battery which communicates with the ground. Near one of the Fig. 43.

extremities of this conductor, we place another conductor *A′ B′*, also insulated, but separated from the first by a small space. At the moment of the discharge, a spark will be seen to escape from the first conductor to the second, and an electroscope, placed upon the latter, will suddenly rise and fall. If we terminate this second conductor by the apparatus represented in figure 41, making its cap communicate with *A′ B′*, and its rod with the earth, the lateral discharge will inflame the gaseous mixture contained in it.

The only danger to be apprehended from lightning rods arises, therefore, from this lateral discharge, which may be diminished at pleasure by increasing the dimensions and the conducting power of the rod. Both theory and experience teach us that this shock is incomparably less than that of the direct discharge; and if it even becomes sensible, what would the discharge itself have been, if there had been no metallic conductor to convey it to the ground?*

96. It has sometimes happened in a thunder storm, that men and brute animals have fallen dead at the instant of an explosion, although they were far distant from the place of the discharge. This phenomenon admits of an easy explanation. Imagine a cloud highly electrified, and of which the two extremities incline toward the earth; they will repel from the ground the electricity of the same kind with that belonging to the cloud, and will attract that of the contrary kind. If from any cause a discharge should suddenly take place at one of these extremities, the equilibrium will be immediately reëstablished at the point of the earth under the other extremity; and this restoration of the equilibrium, if the discharge is very powerful, may be sufficient to occasion the death of animals exposed to it. This phenomenon is called the *electrical returning stroke*. Its effect may be illustrated by the following experiment.

Suspend a living frog by a silk cord, at some distance from the conductor of an electrical machine, as represented in figure 44; let there be attached to one of its legs a very light, flexible wire, communicating with the ground; then put the machine in motion, and as the electricity is developed, from time to time, draw sparks from the prime conductor, by presenting to it a metal rod terminated by

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* See subjoined note on the best form of lightning rods.

a hemisphere. At each explosion, the frog will be seen to quiver, although he is not in the arc of communication; the natural electricities, decomposed by the influence of the electrified conductor, suddenly unite each time that this influence is destroyed, and excite a commotion in the organs of the animal.

These effects take place even after death; to observe them in all their activity, the frog should be killed suddenly; it is then to be skinned and prepared, as represented in figure 45. The irritability is such that the muscular contractions are produced by the influence of a powerful machine, even at the distance of thirty or forty feet. This phenomenon, so simple in itself, shows that the muscular organs of frogs are electroscopes of an extreme sensibility. It will be seen in one of the following sections, that this sensibility has been the occasion of one of the finest discoveries ever made in natural philosophy.

97. We have thus far studied atmospherical electricity only in the violent and transient state in which it appears in thunder storms; but by increasing the delicacy of the instrument employed to make it sensible, we may hope to discover it when it would be inappreciable by ruder instruments. For this purpose we arm the straw or Fig. 46.
gold leaf electroscope with a pointed metallic rod, whose lower extremity is screwed to the end of the stem which communicates with the straws. This rod is commonly about forty inches in length, and is composed of several pieces sliding upon each other, that their length may be varied at pleasure. By the aid of this instrument we discover that the atmosphere when pure is in a constant state of vitreous electricity; but clouds or vapor in the smallest quantity affect this state. For a stronger reason, it changes when the atmosphere is more violently disturbed, as in the case of strong winds, rain, snow, hail, and tempests.

The electroscope of Coulomb, so convenient and delicate in all other experiments, is equally well adapted to the purpose of observing these phenomena. To this end we have only to put its fixed stem in communication with an insulated metallic rod, like that attached to the straw electroscope, and the smallest variations that take place in the atmosphere, will become sensible by their influence upon the movable disc, especially if we begin by charging it with a small quantity of a known electricity. Coulomb even dis-

pensed with the rod or permanent conductor, and fixed a small metallic sphere at the end of a stick of sealing wax, which served to insulate it, and he attached this stick to a wooden pole five or six feet in length. Then, when he wished to try the electric state of the atmosphere, he held the pole up in the air, touching for a moment the small sphere with a metal rod or a simple wire held in the hand. Afterward, withdrawing the rod or wire, he presented the sphere, which, on account of its being insulated, preserved the electricity it had acquired, to the movable circle of the electroscope, upon which it immediately acted. This experiment always succeeded when the electroscope was in an open place, where the air had free access to it, and where the electric state of its strata situated near the ground is not affected by the vicinity of conducting bodies, as trees and the walls of buildings.

98. The intensity of this constant electricity increases as we ascend into the atmosphere; and thus, in order to render it more sensible, Saussure proposed to throw into the air a heavy ball attached to a very fine wire, the lower end of which, being twisted about the stem of the electroscope, adheres to it slightly by its own spring. When the wire is extended by the motion of the ball, it gives to the electroscope the same kind of electricity with the stratum of air to which the ball has risen. But by continuing to move after the wire is entirely taken up, it detaches itself from the stem of the electroscope, which thus remains insulated and charged with the electricity it had acquired.

99. When M. Gay-Lussac and myself ascended in a balloon for the purpose of making experiments, to be described hereafter, when we come to treat of the magnetism of the earth, we also collected the electricity of the atmosphere by methods similar to that of Saussure. A wire 150 feet in length was suspended from our car, being stretched by the weight of a metallic ball. We were by this means in communication with a stratum of air situated 150 feet below us. The atmospheric electricity, collected at the top of this wire, very sensibly affected the electroscope; and being tried with sealing wax, it was found to be resinous, although the weather was perfectly fair.

This result appears to contradict that of Saussure, which has been since confirmed by different observers; but the contradiction

is only apparent; the two results are found in fact to agree. To prove this agreement, let us represent the wire in question by AB; Fig. 47. and at its two extremities suppose two horizontal planes separating the atmosphere into three strata, one above the wire, one comprehended between its extremities and the other below the wire. Now suppose that the atmosphere is really in a state of vitreous electricity increasing with the height. It must be admitted that this electricity is feeble and that its increase is inconsiderable, especially for the distance of 150 feet. This being premised, let us first consider the action of the two extreme strata. We do not now refer to their action by contact; for this must employ a certain time in order to be transmitted, but of the influence at a distance of their free electricities upon the natural electricities of the wire. The upper stratum S, which is in the vitreous state, attracts the resinous electricity of the wire with a force which may be expressed by $+R$, and repels the vitreous with a force which may be denoted by $+V$. The lower stratum S' will do the same in the opposite direction; but its action will be more feeble, for the intensity of the vitreous electricity is supposed to increase with the height. Let, then, r and v be the two forces which it exerts. From this it is evident that the resinous electricity of the wire will be attracted toward the upper part of the wire with an excess of force equal to $R - r$, and the vitreous electricity will be repelled toward the lower extremity with an excess of force equal to $V - v$. Therefore, to us who observed the electricity at the upper part of the wire, it ought to be resinous. To Saussure, who examined it at the lower extremity, it ought to be vitreous.

We have not considered the action of the intermediate stratum AB, upon the electricities of the wire. If this stratum were uniformly electric throughout its whole thickness, its action above and below each half of the wire would counterbalance each other, and there would result no decomposition of the natural electricities of the wire. But the vitreous state increasing with the height, it is evident that the united actions of all the particles of the stratum will produce a resultant of the same nature with the action of the upper stratum, so that this action is thus augmented; and the total effect will also be augmented, if the thickness of this stratum is so great that its action may be compared with those of the upper and lower strata of the atmosphere.

100. We give another experiment, due to M. Hermann, which is explained on the same principles. A very sensible gold leaf electroscope is firmly fixed at a certain height in the air, the weather being fair. It gives no sensible signs of electricity. We carry into the stratum of air, a few feet only above the electroscope, a wire or any other conducting substance, placed horizontally at the extremity of a nonconducting rod; and after having held it for some time in this stratum, we suddenly bring it down till it touches the electroscope; the leaves of which immediately diverge with vitreous electricity. On the contrary, if we carry the insulated conductor into a stratum below the electroscope, and, after suffering it to remain for a time, raise it with a quick motion, it gives to the electroscope the resinous electricity.

These phenomena are explained on the supposition that the movable conductor takes each time the degree of electricity which belongs to the stratum in which it is placed. When brought back so suddenly as to prevent its state from being entirely destroyed by the contact of the particles of air through which it passes, it communicates this state to the electroscope; if it comes from above, it brings with it an excess of vitreous electricity; if from below, it is attended with a deficiency of this same electricity. Let $+E$ be the quantity of free vitreous electricity which the conductor must have in order to preserve an equilibrium in the stratum of air where the electroscope is placed; so that when at $+E$ the particles of air of this stratum neither add any thing to it, nor take any thing from it. It is carried into a higher stratum where it takes $E + dE$; dE denoting the small excess of electricity which it acquires there. If it be then rapidly brought back to the stratum of the electroscope, it will be too much electrified by the quantity dE, and will communicate this to any body with which it may come in contact; it will therefore communicate it to the electroscope, if placed in immediate contact; and the leaves will diverge with vitreous electricity until by the contact of the air, this excess is destroyed. On the contrary, when the insulated conductor returns from a lower region, it possesses the electricity $+E - dE$, less than E by the quantity dE. If it be brought in contact with the electroscope, the instrument will share this state; and the quantity of vitreous electricity which it then possesses will be insufficient

to place in equilibrium the influence of the surrounding atmosphere, and its natural electricities will be decomposed. But the portion of vitreous electricity which this decomposition renders free, will not cause the leaves to diverge, because its repulsive force will be wholly employed to compensate that of the exterior electricity E. The repulsive force, therefore, of the resinous electricity only will exert itself, because there is nothing to compensate it; and the gold leaves will diverge in virtue of this electricity until it has been removed and neutralized by the immediate and successive contact of the particles of air. Experiments of this sort present the singular circumstance of an indefinite medium, the air, the particles of which are each charged with an excess of electricity of the same kind, so that the entire mass of the medium is penetrated with it in a proportion that varies with the height. Hence the different parts of this medium cannot be at rest except by a combination of their repulsive forces with their gravity; and the same condition applies also to the conductors surrounded by them. Thus, for all these conductors, the electric equilibrium will not exist when their natural electricities are completely neutralized, but only when they possess an excess of whichever electricity belongs to the stratum in which they are situated; and this excess is vitreous in a pure atmosphere. If they possess a greater excess of this same electricity, they will act solely in virtue of this excess upon each other, and also upon the particles of the surrounding air; they will therefore mutually repel each other. If, on the contrary, the excess of electricity which they possess is less than that which they would naturally take in the stratum where they are placed, the whole mass of the medium will act upon each one of them in virtue of this difference; and their natural electricities will be decomposed sufficiently to complete what they want of the electricity of the medium. On account of this addition, they will repel the medium as much as the medium repels them, and will suffer from it no action. But they will act upon each other with the excess they have acquired of the opposite electricity, and if the medium is an indefinite fluid composed of particles capable of being electrified by contact, the excess will gradually be dissipated in space. Many curious experiments might be made to determine the laws of electrical equilibrium in circumstances so different from those we are in the habit of considering.

Of Electrical Light.

101. The light which is observed during an electric explosion, was for a long time considered by philosophers as a modification of the electric principle itself, which they supposed to possess the quality of becoming luminous at a certain degree of accumulation. But by observing the light which is disengaged from the air by mechanical pressure, we are led to think that the electric light may have a similar origin, and be simply the effect of the pressure of the air by the electric explosion. This is rendered extremely probable by a critical examination of the experiments that have been performed relating to this subject.* According as the air, which is traversed by the charge, is more or less dense, or as the shock itself is more or less powerful, the colors produced vary from the softest violet to the most dazzling white. This effect takes place in a vacuum of the air pump, and even in that of the barometer. But what is such a vacuum but a space containing the vapor of water or that of mercury, which, as well as air, may disengage heat when sufficiently compressed.

102. Free electricity is attended also with two other effects which have been regarded as belonging to its physical constitution. The first is the sensation, similar to the touch of a spider's web, which electrified bodies produce, when brought near to any part of the naked skin. The second is the odor of phosphorus which is very sensibly emitted by the electric points when they are presented to the organs of smell. But the commotions produced by the Leyden jar and electric batteries prove, that the electricity when in action, violently shocks the organs and excites in them strong muscular contractions. We shall see hereafter other examples of this property. Now, when an electrified conductor is presented near any part of the body, there takes place in this part a decomposition of its natural electricities, and that which is of a contrary nature to the electricity of the conductor, is condensed at the part nearest to the conductor. May not this internal motion, this departure of one

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* See *Biot's Traité de Physique.* Tom. ii. p. 459.

kind of electricity or the introduction of the other, produce in us a certain sensation? And must not the contact of the air alone, which is renewed and electrified upon the parts of the skin where the electricity has become free, excite there some commotion? If this be the fact, there is no reason for going out of our way to imagine particular causes to produce the effect in question; and there is, consequently, no propriety in considering these physical properties as belonging to the nature of the electricity.

103. By varying the direction and the scintillations of the electric light, many interesting results have been obtained. I shall confine myself to describing two which seem to indicate a physical difference between the two electricities.

We arm the prime conductor of an electrical machine, or one of the secondary conductors attached to it, with a metallic point projecting into the air. We then arrange the rubbers in such a way, as to charge these conductors successively with the vitreous and resinous electricity. If the experiment is made in the dark, we observe, in the first case, at the extremity of the point, a conical brush of light attended with a very sensible rustling noise; in the second only a luminous point is seen unaccompanied with any noise.

104. We suspend by a silk thread a piece of pasteboard, as Fig. 48.
a playing card, the two surfaces of which are placed in contact with two metallic points, directed parallel to each other, but not directly opposite at the point of contact. One of these points is made to communicate with the exterior surface of a Leyden jar which is held in the hand, and we touch the other point with the knob of the jar; the discharge is from one point to the other, passing through the card. Now we observe that the place where the card is perforated, is always situated directly opposite the point which communicates with the resinous surface of the jar; and if the experiment is made in the dark, at the moment of discharge, a spark will be seen darting over the surface of the card in contact with the vitreous conductor; while the surface which touches the resinous conductor remains dark. We may preserve the traces of this passage by painting the two surfaces with vermilion, which is found to be altered only on one of them.

This phenomenon and the preceding are very well explained

by supposing that the air affords a much easier passage to the vitreous electricity than to the resinous. Then a point charged with vitreous electricity will dissipate it suddenly, while if it is charged with the resinous electricity, the discharge must take place by the successive contact of the particles of air, which, touching the extremity of the point, carry off the electricity from it. No light will be produced, therefore, except at this extremity; accordingly, in the case of the card, the electricity of the vitreous point only darts into the air to combine with the electricity of the other point; by taking that course which offers the least resistance, gliding at first along the surface of the card and piercing it at the moment it is opposite to the other point, the attraction being then the most powerful. M. Tremery, who first explained the phenomenon in this way, contrived to weaken the influence of the restraining force, by diminishing the density of the interposed air; and this he did by repeating the same experiments under the receiver of an air pump. He thus found that the hole in the pierced card approaches nearer to the middle of the interval between the two points, according as the surrounding air becomes more rare, and thus opposes a less resistance. This result seems to agree with the supposition of an unequal restraining power being exerted upon the two electricities. We shall hereafter make known phenomena which prove the existence of a similar inequality in other substances besides the air. But this inequality is not sensible, except for electric charges having a very feeble repulsive force; and it is very difficult to conceive how it can exist in the air, even for the strongest charges, when all other phenomena seem to indicate that the resistance opposed by the air, to the expansion of the electricity, arises solely from its pressure. It would be well, therefore, to repeat the experiments under new circumstances, for instance, in different media, that, if possible, these apparently contradictory facts may be reconciled.

Of the different Methods of developing Electricity.

105. To study the different properties of the electric fluids and establish their respective characters, it is sufficient to have some certain and easy method of exciting them. This is commonly found

in friction ; and as its effects admit of being indefinitely augmented, in the former part of this treatise we have described and used no other method. But it now becomes necessary to make known other means of acting upon bodies, by which their natural electricities may be separated ; for it is only by experiments of this sort that we can discover in what manner the two electric principles are connected with the natural constitution of bodies.

In the first place, I have said, in speaking of friction, that apparently the most trifling circumstance determines a body to take one rather than the other electricity, when rubbed against another body. For example, if we rub against each other two silk ribbons AB, $A' B'$, cut without any distinction from the same piece, placing them crosswise in such a way, that one of them AB shall rub successively throughout its whole length, while $A' B'$ is rubbed only in the part C, the former always takes the vitreous, and the latter the resinous electricity. In this case, the electricity is determined merely by the manner of the friction. But the higher or lower temperature of one of the two bodies has an important effect upon the kind of electricity which it acquires, as is proved by Bergman. In the preceding experiment, for instance, if the ribbon AB, which rubs successively throughout its whole length, is at first heated to a high degree, and the friction is not continued so long as to reduce it to nearly the same temperature with $A' B'$, this circumstance will have more effect than the manner of the friction, and AB will now take the resinous, and $A' B'$ the vitreous electricity. After the ribbon AB has become cold, or when the two ribbons have come to the same temperature, things will return to the state first described ; and in the passage from one of these states to the other, there will be a point at which a state of indifference will be manifested. To conduct experiments of this sort with all possible delicacy, and to be able to follow with certainty all the variations of the electric state, it is necessary, after each operation, to present instantly each of the bodies upon which we operate, to a very sensible gold leaf electroscope, merely touching the knob with the body whose electric state we wish to know. We may also employ to advantage Coulomb's silk thread electroscope. From a series of curious experiments made with this instrument by that ingenious philosopher, he thought he had discovered a general law, which, although somewhat indefi-

nite in its expression, seems nevertheless to harmonize with too many facts not to include the germ of a general truth. It is enunciated as follows; when the surfaces of two bodies are rubbed together, that body, the integrant particles of which are least removed from each other, and which vibrate least about their natural positions of equilibrium, seems, by this very circumstance, to be the more disposed to receive the vitreous electricity. This tendency is increased if the surface suffers a momentary compression. Reciprocally, that body, the particles of which are most removed asunder by the roughness of the other, or from any other cause, is on that account the more disposed to take the resinous electricity. This tendency is increased when there is a real dilatation of the surface. Heat, by separating the particles of the body, appears to act in this way, and to dispose it to the resinous state. It is necessary to remark that these conditions are not presented by Coulomb as absolute, but merely as relative; that is, they simply dispose bodies to such an electric state, but do not determine them to it necessarily; for doubtless the very nature of the bodies thus rubbed, has an influence upon the phenomenon; but this influence Coulomb did not attempt to estimate.

106. The preceding principle applies very well to an experiment made by M. Libes long after Coulomb had advanced these ideas. The experiment is as follows. We take a disc of metal which is held insulated by a glass handle, and press it upon some gummed taffeta, either simple, or consisting of several thicknesses. The gum with which the taffeta is covered, is capable of being compressed, and it is on this account that it adheres to bodies, the asperities of which leave their impressions upon its surface. According to Coulomb, it is now in a condition to facilitate the development of the vitreous electricity; and we in fact find this kind of electricity, when we remove the disc; and the disc possesses a corresponding excess of resinous electricity. The effect is more marked according as the pressure is greater. It ceases when the taffeta has lost its glutinous quality which rendered its surface easily compressible. Friction is not concerned in this phenomenon; for if, instead of pressing the disc upon the taffeta, we lay it lightly upon its surface, and move it backward and forward in order to produce friction, the disc takes the vitreous electricity, and the taffeta

the resinous ; a precisely opposite effect to that produced by pressure.

107. The curious remark of M. Libes has been extended by M. Haüy to several mineral substances, with this striking peculiarity, that some of them take the electric state with the slightest pressure, and afterward obstinately retain it. For instance, the rhomboidal carbonate of lime, commonly called Iceland spar, becomes electric when merely pressed for an instant between the dry fingers ; its electricity is quite sensible, and of the vitreous kind, which it retains with much force ; for it does not yield it to a conducting body which communicates with the ground, nor even when it is immersed in water. Other minerals possess this property in a less degree ; and some appear to be altogether destitute of it. But M. Becquerel has shown that the exception is only apparent, and is owing to this, that the bodies in question have not, like the first, the property of retaining the electricity which they have once acquired ; and hence, to render it sensible, it is necessary to insulate them during the contact. For this purpose, he fixes the substance to be examined to one end of a glass rod, the other end being terminated by a handle of dry wood, in order that it may be held in the hand without being electrified by friction. This little apparatus is then to be left for some time without being touched ; in order to ascertain that it is not electrified, he next presents it to the disc of Coulomb's electroscope, charged with a known electricity ; and when assured that it is perfectly neutral, he presses the mineral with the finger, or upon any solid body, whether insulated or not. Proceeding in this way, he found that not only minerals, but all substances of whatever nature, being insulated and pressed against each other, come from the pressure in different states of electricity, the one with an excess of vitreous, the other with a corresponding excess of resinous electricity. If one only of the two bodies is insulated, that only preserves the electricity which the pressure has given it, and the other parts with it to the ground, unless its substance happen to be of a non-conducting or imperfectly conducting nature, which permits the electricity of its surface to fix itself by the decomposition of the natural electricities of the interior laminæ. This appears to be the case with the Iceland spar. The absolute intensity of the effects is different in different substances ; and in some, they are so feeble that they

can be made sensible only by particular precautions; the most essential of which is to give to the bodies employed, the form of small discs of a few hundredths of an inch in diameter. Their electric properties are also very much heightened by being warmed. Some substances, as tinder and elder pith, manifest no sensible effects without having their temperature raised.

108. It will be seen in the following section, that according to a very beautiful discovery of Volta, bodies of whatever kind being placed in contact, are found, upon being separated, to have different electrical states; but the phenomena observed by M. Becquerel seem, by their intensity and by many circumstances which attend them, to be of another kind. For instance, if we press an insulated disc of cork upon the palm of the hand, or the living hair upon a wooden table or upon an orange peel, and after having withdrawn it, bring to it the knob of the gold leaf electroscope, two or three successive pressures, and sometimes a single one, will be sufficient to give to the leaves a considerable divergence; while it is necessary to arm the electroscope with a condenser to render sensible the electricity developed in it by simple contact. Moreover, the facility with which substances admit of being compressed and afterwards restore themselves, very much favors this development of electricity by pressure. Much is excited, for instance, by pressing an insulated disc of cork upon a mass of leaves stitched one upon another. The imperfect liquids which are capable of being compressed and of restoring themselves afterward, are equally adapted to produce these effects, as may be seen by pressing the insulated disc of cork upon some oil of turpentine thickened by boiling, which forms a sort of varnish of imperfect fluidity. M. Becquerel has remarked also, that in these experiments, as in that of M. Libes, the electricity developed by pressure becomes more intense according as the substances adhere more closely to each other, when pressed together, and require a more sensible effort to separate them. Generally, this development appeared to him to be modified by an infinite number of circumstances, such as the polish of the surfaces, the more or less moist state of the air to which they are exposed, and their more or less recent separation.

109. M. Dessaignes long ago made known a fact which seems to have much analogy with the preceding; it consists in this, that

if a rod of glass or sealing wax be immersed in mercury, it usually comes out electrified, whether it is entirely immersed, or merely placed upon the surface of the liquid, or is employed to give a smart blow to this surface. The most simple means of verifying this fact, is to present the rod, after it is withdrawn from the mercury, to the disc of Coulomb's electroscope, previously charged with a known electricity. The effect is particularly remarkable when gum lac is used, for the electricity which it acquires by a single immersion is stronger than that produced by friction.

M. Dessaignes has remarked variations in the nature and intensity of the electricity acquired by the immersed rod, which seemed to him to depend on the state of the atmosphere, as to humidity, temperature, and pressure. If the electroscope made use of have sufficient sensibility to indicate perfectly their variations, we might with some probability attribute them solely to the hygrometric state of the surface of the rods, which, according to the relation it bears to that of the surrounding atmosphere, would cause them to emit or condense vapor; in fact, Volta and several others after him, have affirmed that aqueous vapor, in forming, absorbs vitreous electricity.

110. The sudden separation of the parts of bodies, when observed in the dark, is often accompanied with a more or less permanent disengagement of light. This effect is apparent, for instance, when a piece of sugar is crushed, even though the sugar is immersed in water; in this case it is sudden like the blow which produces it. The phosphorescence is more permanent in chalk when pounded with a hammer. May it not be that the light thus disengaged, indicates, when it is sudden, a decomposition of the natural electricities? For example, when we separate rapidly in the dark, the leaves of a piece of Siberian mica the extremities of which have been previously fixed to non-conducting rods, a vivid bluish flash of light is seen upon the separating surfaces. Now if we present these surfaces to the electroscope after their separation, it is found, as was observed by M. Becquerel, that one is electrified vitreously, and the other resinously. Why may it not be the same in other cases of violent separation? Quantities of electricity too small to be appreciated by our best electroscopes, are yet perhaps capable of disengaging by their development a visible light.

The account which I have now given of these various experi-

ments, shows that the development of the electrical principles is still but imperfectly understood; but we must, at the same time, perceive that it affords one of the finest subjects of physical enquiry.

Of the Development of Electricity by simple Contact.

111. We now proceed to consider the development of electricity by simple contact. This branch of Natural Philosophy, which dates only about fifty years back, presents the contrast of a great discovery, resulting from an accident, and of one still greater, made directly and carried out by the most rigorous inductions and experiments.

It was about the year 1789 that the first phenomena of this sort presented themselves. Galvani, professor of Natural Philosophy at Bologna, instituted some inquiries on the excitability of the muscular organs by electricity. He employed in his experiments frogs recently killed and skinned, of which he divided the spine in order to
Fig. 50. insulate and lay bare the lumbar nerves. That he might manage them conveniently, he introduced into the remaining part *E* of the spine, a copper wire bent in the form of a hook. It accidentally happened one day that several frogs were suspended by these copper hooks from the iron balcony of a terrace; at that instant their feet and legs, which also lay in part upon the iron, became spontaneously convulsed; and the effect was the same at every new contact. Galvani perceived the importance of this phenomenon, and set himself to determine its essential circumstances. He saw, in the first place, that instead of holding the frog by the hand, it might be laid on an iron plate, and that applying to this plate the copper hook, the convulsions still took place. He next perceived that the whole was reduced to the establishing a communication between the muscles and nerves of the frog by a metallic arc. He observed that the convulsions still took place, when this arc was of a single metal, but that they were then very rare and very feeble, and that to render them strong and permanent, it was necessary to employ two different metals in contact. This condition being fulfilled, the communication might be completed by any substances whatever, provided they were conductors of electricity.

He introduced into the chain of communication other animal substances, and even living persons who held each other by the hand; convulsions still took place. Now Galvani had recently observed, that the electricity developed by the ordinary methods produced similar effects upon the organs of frogs, when they were exposed to its influence. A most evident analogy seemed therefore to lead directly to the conjecture that the convulsions produced by the contact of the heterogeneous metals were also the effect of some electrical current which this contact developed. Nevertheless he did not draw from it this simple conclusion; he thought he saw in it the extraordinary effect of a new source of electricity, which he called *animal electricity*, and which, existing originally in the muscles and nerves, circulated when these parts were placed in communication by a metallic arc, or by any good electrical conductor. Galvani vainly attempted to compare this action to that of the Leyden jar; but on looking at the work itself in which this hypothesis is advanced,* it is apparent that he was not acquainted with the true theory of electrical influence, and that, explaining the circumstance in this way, he was led to adopt theories that had little of reason or ingenuity to recommend them. We are thus compelled the more to admire the rare sagacity and true genius by which he seized, as if by divination, and varied with so much skill, the extraordinary phenomenon of the seemingly spontaneous convulsions which he had accidently observed.

When these new facts were made known in Italy, they excited general admiration, and all were inclined to favor the views of Galvani. But the celebrated Volta of Pavia had no sooner repeated the experiments, than he drew from them altogether different conclusions; and it may be said that accident itself, by making known these phenomena subsequently to the sensible effects of artificial electrical influence, had thus sought to indicate their true source. Therefore Volta had no doubts with respect to its nature. Conceiving that the cause of these motions, whatever it was, must be very subtile, since they were produced independently even of the will of the observer, he set himself to determine by exact experiments the precise quantity of electricity necessary to excite convul-

* *De Viribus Electricitatis in Motu Musculari Commentarius.*

sions in the organs of frogs, by causing a discharge to pass through them. He thus discovered that this quantity was exceedingly minute, and scarcely sufficient to produce a sensible divergence in the straws of the delicate electroscope which he made use of. This result being obtained, he compared it with the other fact established by the experiments of Galvani himself, that the contact of two or more heterogeneous metals was, or at least thus far appeared to be, necessary to excite the convulsions; and he hence drew this conclusion, that the mere contact of the heterogeneous metals was the unperceived circumstance, which caused the sudden development of electricity. In following out this truly fundamental idea, Volta collected under one point of view all the experiments hitherto made by Galvani, and he pointed out the means of reproducing the same effects in a certain manner, and with the highest degree of energy. In making use of different metals, he observed that the best was zinc placed in contact with silver or copper, although the convulsions might also be produced by an arc composed of any two metals whatever.

112. From the preceding observations, we infer that the best preparation for repeating the experiments of Galvani is the following. Take a frog and separate the hind legs and a part of the spine; next remove the flesh and all the parts which cover the Fig. 51. lumbar nerves, denoted by *NN*. Then enclose these nerves in a small strip of copper or zinc; place the frog, thus prepared, upon a nonconducting support, for instance, upon a pane of glass varnished with gum lac; and, taking a piece of any other metal, bent into the form of an arc of a circle, place one of its extremities upon the armature of the nerves, and the other upon the muscle of the thighs; the convulsions will immediately take place, not only in the leg which has been touched, but also in the other. The frog retains its susceptibility of these motions some time after death; and it retains it the longer according as it has been less excited. When beginning to decline, it may be restored by the application of such stimulants as tend to increase animal irritability. The same is to be observed also with respect to the convulsions which are produced in the organs of frogs by the influence at a distance of common electricity; and the only conclusion to be drawn from all we have said is, that these organs, when fresh, sensibly indicate the smallest discharges of electricity.

113. Guided by the fundamental idea which thus revealed the secret of this kind of action, Volta ascribed to the same cause several phenomena of sensation, which had not as yet been attended to, doubtless because they stood alone, but which, when accurately examined, are found to refer themselves, in the most evident manner, to the action of several metals in mutual contact. For example, he recalled to mind an experiment described in an old work, entitled, *Theory of Pleasure*, and which is extremely well adapted to show this influence. Take two pieces of different metals, one of silver or copper, and the other of zinc, for instance. Place one of these pieces above, and the other below the tongue, in such a manner that they may project a little beyond the tip of the organ. As long as the pieces are separated from each other by the tongue, no effect is produced. But when they are made to touch each other, a peculiar taste is perceived very much resembling that of the sulphate of iron. Here, according to Volta, electricity is developed by the mutual contact of the two pieces; and the surface of the tongue, which is covered with nervous papillæ of an extraordinary sensibility, serves as a conductor. Sometimes, also, the excitation is transmitted to other nerves; and if the person is in the dark, he perceives a flash of light in his eyes. All the sensible parts of animals are capable of being affected by such an arrangement. This susceptibility has become in anatomy the certain and delicate means of discovering the most subtile nervous fibres in different parts of the organs of animals.

114. Galvani endeavored to support his hypothesis of an animal electricity in opposition to the Pavian professor; he urged as an objection to the theory of the latter, the convulsions excited by an arc of a single metal, and endeavored to vary the circumstances of this experiment. For instance, after a frog is quickly prepared in the manner we have just described, if it be immediately laid upon a bath of very pure mercury in such a way as to form a communication between the nerves and muscles, convulsions are usually exhibited. Volta answered that, even in this case, there might be some heterogeneity in different parts of the conducting arc, either upon the surface of the mercury or by the contact of the metals, used in preparing the animal. Indeed the smallest difference in the substances employed to form the communication is sufficient to

cause convulsions, when they do not take place without this difference. For example, if we arm the nerves of a frog with a sheet of impure lead, such as is made use of by glaziers, and then complete the communication by an arc of the same metal, taken from the same leaf, and consequently of an exactly similar nature, effects are rarely produced. But if we complete the communication with purified lead such as assayers use, the armature remaining the same, convulsions will immediately take place; and it is only necessary to rub the arc of a single metal with another metal in order to make it sufficiently heterogeneous, as has been shown by M. Halle. Nevertheless, Galvani did not yield to these arguments; he carried his precautions so far as to prepare the organs of the frog with plates of glass, wrought into the shape of a knife. He still obtained convulsions with an arc of a single metal, but only in the case which we have mentioned, that is, when the animal is very fresh, and in an extremely irritable state. Finally, after having prepared the frog with all this care, he succeeded in producing the contractions by the mere contact of the muscles and nerves of the animal itself, without employing any intervening substances whatever.* But if, as Volta affirmed in reply, electricity is developed by the mere contact of two metals, it is equally possible that it may be developed by the contact of any two heterogeneous substances, as the muscles and nerves. And if this action is much more feeble than that of one metal upon another, it will be necessary, in order to detect it, to employ a still more sensible electroscope, such as the organs of the frog appear to be immediately after death. This new fact observed by Galvani serves, therefore, to generalize the idea of Volta, instead of overthrowing it.

115. It became necessary, however, to settle the question by

* To produce this effect, it is necessary to prepare the frog very quickly, in the way above described; then taking it in one hand by one of its feet, we hold it in an inverted position, so that the lumbar nerves hang down, stretched by the weight of the small fragment of the spine which remains attached to them. Then, taking in the other hand the other foot, we twist it in such a manner as to bring the thigh in contact with the lumbar nerves. If the frog is very irritable, the convulsions are immediately produced; nevertheless, it is sometimes necessary to make trial of several before we succeed. This experiment has been contested, but the result is very certain if the precautions above given are observed.

actual experiment. For this purpose Volta made use of two metallic discs, one of zinc and the other of copper, about two inches in diameter, the plane surfaces being very true and unvarnished, and provided with non-conducting handles for the purpose of bringing them together and separating them without touching them immediately. These discs being brought toward each other till they touch, are then to be separated and withdrawn in a parallel direction; and their electric state tried by means of a straw or gold leaf Fig. 52. electroscope. But as the electricity which is developed by a single contact is always extremely feeble, we do not try directly its repulsive force upon the electroscope; but we previously arm this electroscope with a condenser; we then accumulate upon it the electricity of several contacts, by making its upper plate communicate with the ground, and touching the lower plate with the metallic disc whose electricity we wish to try, this lower plate communicating with the straws. We then withdraw the disc, touch it as well as the other to restore them both to their natural state, and place them again in contact; we then separate them and bring again to the condenser the one we wish to try. After seven or eight contacts of this sort, if we remove the upper plate of the condenser, the straws will diverge very sensibly in virtue of the electricity imparted to the lower plate, by the successive contacts of the metallic disc; and we then determine the nature of this electricity. That the experiment may succeed, it is necessary that the plates of the condenser should be without varnish upon the surfaces on which the electricity is deposited; for in this state of weakness, the smallest obstacle would be sufficient to prevent its introduction. It is necessary, moreover, for the sake of accuracy, that each plate should be made of the same metal as the disc with which it is touched; otherwise the electric influence of this new contact would combine with the effect of the first and modify the result. Nevertheless, when it is impossible to comply with this condition, we may effect the same purpose, by placing upon the plates, at the point where they are touched, a small strip of paper moistened with water or any liquid that conducts electricity. For, as we shall presently see, the contact of the paper, moistened with such liquid, does not exert upon the metals any sensible electrical influence. Let us suppose these precautions to have been taken, and for the sake of distinctness

that the plates are one of copper and the other of zinc. If it is the disc of copper which has been made to touch the lower plate of the electroscope, the electricity which causes the straws to diverge will be resinous; if, on the other hand, the zinc has been used, the electricity will be vitreous. Thus these two metals, being insulated in their natural state, are brought by simple contact into different electrical states; the copper acquiring an excess of resinous electricity, and the zinc a corresponding excess of vitreous electricity.

The experiment may be repeated in different ways. Let neither of the plates of the condenser communicate with the ground; let them both be insulated upon the electroscope, but each time that the two discs are separated, touch each of the plates at the same time with that disc which is of the same metal with itself. As the free electricities which they receive are of different kinds, they will mutually attract each other, and become fixed upon the contiguous surfaces of the plates. After several contacts of this sort, separate the plates, and each of them will be found to be charged with the electricity of the disc which was made to touch it.

116. It might be imagined that the electricity which is developed in this case depends on a compression of the discs, the one against the other, like that which generally developes itself by the compression of heterogeneous substances. But it is easy to prove that the action occasioned by the contact of metals is quite different, and is excited by a reciprocal influence which decomposes their natural electricities. To establish this important fact Volta made the following experiment. He formed a metallic plate with two pieces Z, C, the one of zinc, the other of copper, soldered end to end.
Fig. 53. Then, taking between the fingers the extremity, of the zinc end, he touched with the other extremity, of copper, the upper plate of the condenser, also of copper, the lower plate communicating with the ground. After the contact, if the plate touched be removed, it is found to be resinously electrified. This phenomenon is perfectly conformable to the preceding experiment; it is to be observed, however, that we have no longer to fear the effect of pressure or separation between the particles of zinc and those of copper, since their juxtaposition is permanently established, and since the contact with the condenser takes place between copper and copper, and therefore can develope no new electricity. In order that the elec-

tricity thus produced by a single contact should be very sensible, it is necessary that the condenser used should be much larger than that of the electroscope and of considerable condensing force. We also obtain similar results without touching the zinc plate with the fingers, it being held merely by glass rods or any other nonconducting substance. But in this case, since the plate in question no longer communicates with the ground, it is necessary that it should be placed in contact with some body of a large capacity, from which it may draw the electricity which it is to furnish to the collector plate of the condenser. This is done either by giving a larger surface to the zinc plate, or which is better, by connecting it with the interior of a large Leyden jar, armed within by a plate of zinc, the exterior surface of which, being also armed with some metal, is placed in communication with the ground.

117. The metals, and a great number of substances not metallic, act upon the natural electricities of each other, like zinc and copper, when they are placed in contact; and it is extremely probable that this property extends in different degrees to all bodies in nature. Among the various combinations that may be formed there are some in which the development is the most active, and others where it is the most feeble or even insensible. In the first class are the heterogeneous metals, when placed in contact with each other; in the latter are pure water, saline solutions, and even the acid liquors, when placed in contact either with one another, or with metals.

In reference, however, to these cases of supposed electrical excitation by the contact of different metals, it is found that the most oxidizable metal is always *positive*, in relation to the least oxidizable metal, which is negative, and the more opposite the metals in these respects, the greater the electrical excitation. Thus if the metals be arranged in the following order—platinum, gold, silver, mercury, copper, iron, tin, lead, zinc, potassium; each will become *positive* by the contact of that which precedes it, and negative by the contact of that which follows it; and the greatest effect will result from the contact of the most distant metals. Here we have strong presumptive evidence in favor of a chemical cause as the source of electricity, for it is not produced by the most dissimilar conductors either of heat or of electricity, but by those which are most opposed

in the facility with which they are acted upon by the generality of chemical agents.

118. Such were the views originally entertained by Volta in regard to the newly discovered power, and which were received with some qualifications by Biot and other eminent physicists. This theory, which referred the whole effect to the simple *contact* of different substances, was adopted with some modifications by Sir H. Davy, who seems to have considered the electric state of the pile as due partly to the contact of the opposed metals, and partly to the chemical action of the interposed liquid. At the present day Volta's hypothesis has but few supporters. Mr. Faraday has satisfactorily shewn that electricity is produced in voltaic arrangements independently of contact, and apparently by chemical action only; for he found that a single pair of plates, so disposed as to avoid metallic contact, and every other source of electricity except chemical action, produced a current sufficient to affect a galvanometer. Wollaston attributed the new kind of electricity exclusively to chemical action, explaining the action of the dry pile by the chemical action of the moisture hygrometrically retained by the paper. The electrical equilibrium is so easily disturbed, or in other words, there are so many causes of electrical excitation, that it becomes difficult to separate them and refer to each its proper influence. One cause, therefore, being fairly established, does not operate to the exclusion of the rest; though it would appear from the careful experiments of Fabroni, De la Rive and Faraday, that whenever electricity is developed during metallic contact, it is owing to some chemical action, undergone by the most oxidizable metal. One thing appears to be demonstrated, that no chemical action occurs, unaccompanied by disturbance of electric equilibrium and consequent development of free electricity.

Voltaic Batteries.

119. We have thus far considered only the elementary form of Voltaic electricity, as it is derived from a single pair of plates. This is called a simple Voltaic circle. Compound arrangements, or voltaic batteries, are made by a combination of several simple circles.

If we make two circular plates to adhere together by a strong pressure, one being of zinc and the other of copper, and if, after having placed them upon the hand with the copper side downward, we cover the zinc face with a moist conductor, the contact of which does not disturb the proper electric state of the pair, with a piece of cloth, for instance, saturated with water or a saline solution, any conducting bodies which may be placed above this system will partake of the excess of vitreous electricity belonging to the zinc face and the moist body which covers it. If, therefore, upon this first system, we place another of the same kind, in such a way that its copper face shall rest upon the moist cloth, this second system will, as a conducting body, partake of the excess of vitreous electricity belonging to the first zinc surface; and moreover, the second piece of zinc will take a new excess of electricity, also vitreous on account of its contact with the copper to which it adheres. Adding thus successively several similar systems to each other, we shall have an apparatus in which the electric state of the successive pieces will go on augmenting from the bottom upwards, according to the number of pairs which are placed upon each other. Such is the admirable instrument universally known at present under the name of the *Voltaic Pile* or *Voltaic Apparatus*.

Instead of placing the metallic plates upon each other in a vertical column, they may be placed horizontally, and parallel to each other upon insulating supports, for instance, upon rods of varnished glass. Then, instead of interposing between them pieces of cloth, cells may be formed from one to the other to receive the liquid which is to serve as a conductor; this arrangement is called the *Galvanic* or *Voltaic Trough*. We may also solder together, end to end, plates of copper and zinc inclining them a little at the soldered point, in such a way that each metal may be immersed in a glass or porcelain vessel, partly filled with the conducting liquid. A series of such vessels forms an electromotive chain, the extremities of which may be made to meet for the convenience of experiments. This Volta called *a crown of cups*. Fig. 59. Fig. 60.

Comparing the charges obtained with piles of the same number of plates connected by moistened conductors of different kinds, it is found that water, weak acids, moist saline solutions, and generally substances of a high conducting power, give the same sensible quan-

tity of free electricity, and give it by a contact apparently instantaneous. Indeed, for bodies of the greatest conducting power, we may very much increase or diminish the extent of touching surface, without any apparent variation of the charge, undoubtedly on account of the extreme facility with which the surface transmits the electric current; and hence Volta supposed that they perform the office of conductors merely, and that their contact, or their chemical action, is not the determining cause of the development of electricity. Nevertheless, we also find liquids with which the charges are unequal, for the same number of pairs, either because they too much weaken the conducting power by their interposition, as we shall show hereafter, or because they modify the conditions of the electric equilibrium by their contact, or by the nature of the combinations which they form with the other parts of the apparatus. All these varieties have presented themselves in the numerous experiments made by philosophers since the time of the first use of the instrument.

120. A more favorable arrangement of the voltaic apparatus for producing powerful chemical effects, is that in which the electric charges developed instantaneously and continually by the action of the metallic plates of each pair, shall pass in the freest manner possible, through the liquid conductors which separate them. It will, therefore, be necessary, in the first place, to choose those liquids which transmit the electricity most perfectly; such appear to be the nitric and sulphuric acids diluted with a large quantity of water. It will also be useful to employ metallic plates of a large surface. This large extent is not necessary indeed, in the parts where the two metals of each pair mutually touch each other; for it appears that the electricity developes itself there instantaneously, and spreads itself with so much rapidity, that the smallest surface in metallic contact is sufficient to maintain the most extended liquid masses and those of the greatest conducting power under a given repulsive force. But for this very reason, in the contact of the plates with the liquid, the extent of surface will have a very great influence upon the absolute quantity of electricity transmitted in equal times, and therefore, the effects will increase with the dimensions. Finally, the liquids interposed should be kept, as far as possible, in their primitive state of composition, or of conducting power, while the

apparatus is in use; and as this condition cannot be fulfilled by merely increasing the quantity, which would render the apparatus inconvenient in practice, and would even be injurious, if we augmented the intervals by which the metallic pairs are separated, it is necessary to provide means by which the liquid conductors may be easily renewed, and brought in contact with the plates only at the moment when we wish to make use of them. We obtain all the advantages above-mentioned by forming the apparatus of a series of double plates similar to that already described. We fix all the pairs parallel to each other upon the same piece of wood, made strong enough to support them without bending; and we arrange below an equal number of wooden, porcelain, or glass troughs, filled Fig. 68. with the conducting liquid. If we wish to make use of the apparatus, we lower the wooden bar, and each pair is immersed in the corresponding trough. When our experiments are completed, we raise the bar, and the troughs filled with liquid remain prepared for another experiment; but if we think that the liquid needs to be renewed, we empty the troughs and fill them again. Dr. Wollaston constructed a battery in which he availed himself of the discovery that the maximum effect was produced with the same amount of metal, when the copper plate was made considerably larger than the zinc. A simple voltaic circle of this kind may be seen on figure 64, for a description of which we refer to a future paragraph.

121. The name of Calorimotor is given by Dr. Hare to an instrument invented by him, in which the calorific effects are accompanied with a feeble influence upon the electroscope.

A, *a*, represent two cubical vessels twenty inches square, *b b b b*, Fig. 74. a frame of wood containing twenty sheets of copper, and twenty sheets of zinc, alternating with each other, and about half an inch apart, *TTtt* masses of tin, cast over the protruding edges of the sheets, which are to communicate with each other. Fig. 74′ represents the mode in which the junction between the several sheets and the tin masses is effected. Between the letters *z z*, the zinc only is in contact with the tin masses. Between *c c*, the copper alone touches. It may be observed, that, at the back of the frame, ten sheets of copper between *c c*, and ten sheets of zinc between *z z*, are made to communicate by a common mass of tin extending the whole length of the frame between *TT*; but in front, as shown

on figure 74, there is an interstice between the mass of tin, connecting the ten copper sheets, and that connecting the ten zinc sheets. The screw forceps, appertaining to each of the ten masses, may be seen on either side of the interstice; and likewise a wire for ignition held between them. The application of the rope, pulley, and weights is obvious. The swivel at *S*, permits the frame to be swung round and lowered into water in the vessel *a*, to wash off the acid, which, after immersion in the other vessel, might continue to act on the sheets, encrusting them with oxide. Between *p p*, there is a wooden partition, which is not necessary, though it may be beneficial.

"Volta considered all galvanic apparatus," says Dr. Hare, "as consisting of one or more electromotors, or movers of the electric fluid. To me it appeared, that they were movers of both heat and electricity; the ratio of the quantity of the latter put in motion, to the quantity of the former put in motion, being as the number of the series to the superficies. Hence the word *electromotor* can only be applicable, when the caloric becomes evanescent, and electricity almost the sole product, as in De Luc's and Zamboni's Columns; and the word *calorimotor* ought to be used, when electricity becomes evanescent, and caloric appears the sole product.

"The heat evolved by one galvanic pair has been found by the experiments which I instituted, to increase in quantity, but to diminish in intensity, as the size of the surfaces may be enlarged. A pair containing about fifty square feet of each metal, will not fuse platina, nor deflagrate iron, however small may be the wire employed; for the heat produced in metallic wires is not improved by a reduction in their size beyond a certain point. Yet the metals above mentioned are easily fused or deflagrated by smaller pairs, which would have no perceptible influence on masses that might be sensibly ignited by larger pairs. These characteristics were fully demonstrated, not only by our own apparatus, but by those constructed by Messrs. Wetherill and Peale, and which were larger, but less capable of exciting intense ignition. Mr. Peale's apparatus contained nearly seventy square feet, Mr. Wetherill's nearly one hundred, in the form of concentric coils; yet neither could produce a heat above redness on the smallest wires. At my suggestion, Mr. Peale separated the two surfaces in his coils into four alternating,

constituting two galvanic pairs in one recipient. Iron wire was then easily burned, and platina fused by it. These facts, together with the incapacity of the caloric fluid, extricated by the calorimotor, to permeate charcoal, next to metals the best electrical conductor, must sanction the position I assigned to it, as being in the opposite extreme from the columns of De Luc and Zamboni. For, as in these the phenomena are such as are characteristic of pure electricity, so in one very large galvanic pair, they almost exclusively demonstrate the agency of pure caloric.

"When the instrument is lowered into a solution, containing about a seventieth of sulphuric acid, a wire placed between the poles, becomes white hot, and takes fire, emitting the most brilliant sparks. In the interim an explosion usually gives notice of the extrication of hydrogen in a quantity adequate to reach the burning wire. Immediately after the explosion, the hydrogen is reproduced with less intermixture of air, and rekindles, corruscating from among the forty interstices, and passing from one side of the machine to the other, in opposite directions and at various times, so that the combinations are innumerable. The flame assumes various hues, from the solution of more or less of the metals, and a froth, apparently on fire, rolls over the sides of the recipient. When the calorimotor is withdrawn from the acid solution, the surface of this fluid for many seconds, presents a sheet of fiery foam.

"I ascertained, that the galvanic fluid, as extricated by this apparatus, does not permeate charcoal. This demonstrates, that it cannot be electricity, as of the latter, charcoal is, next to metals, the best conductor."

122. We have another modification of the voltaic apparatus, invented likewise by Dr. Hare, to which he has given the name of *deflagrator*. It consists of two pairs of troughs, each ten feet long, the two of each pair being joined lengthwise, edge to edge, so that when the open side of the one *AA*, containing the plates, is vertical, the open side of the other *BB*, without plates, is horizontal, and *vice versâ*. The acid liquor being poured into the trough *BB*, by a partial revolution of the apparatus, it is made to flow into the trough containing the plates. Each pair of troughs turns on pivots *D*, *D*, supported by frame work *C*, *C*. The pivots are of iron, coated Fig. 75.

with brass or copper, and a communication is made between them, and the voltaic series within, by strips of copper.

The pairs of the series consist of copper cases about seven inches long, by three inches wide, and half an inch thick, and each containing a plate of zinc equidistant from the two sides, kept from touching the copper by grooved strips of wood. Each plate of zinc *z*, is soldered to the next case of copper on one side, as represented in figure 75′. The copper cases are open only at the bottom and top, and are kept separate from each other by pieces of wood.

123. De Luc formed an electric column in this way. He took thin silver and zinc discs, not more than three eighths of an inch in diameter, piled them in regular order, with the intervention of writing paper, to the number of some thousands. These discs may be formed of strongly gilt paper and zinc first cut out with a punch, and enclosed in a glass tube fitted with brass caps at each end, and carrying screws by which they can be pressed together. This arrangement is sometimes called the dry pile. But it depends on moisture as much as any other battery. If the paper be dried artificially, the column will be inactive, but its ordinary hygrometric moisture will be sufficient to throw it into a strong excitement. No current, however, is established under these circumstances, which can be detected by any chemical decomposition, though the instrument will affect the gold leaf electromoter. Hachette constructed a similar pile out of metallic plates, separated by a simple stratum of flower paste mixed with sea salt.

The column of Zamboni was slightly different from this. His plates consisted of discs of paper, gilt or silvered on one side, and covered on the other with a stratum of pulverized oxide of manganese. The gilt side of one disc touches the opposite side of the next disc. The interposed paper acts the part of a conductor. Here as with the paste pile only electrical signs were produced, but no chemical action or physiological effect.

Various other forms of the voltaic battery have been contrived by Mr. Daniells, Mr. Faraday, and others; but a detailed account of them would fill too large a space. The sustaining batteries of Sturgeon, Daniells and Mullins will receive some notice when we come to Electro-dynamics.

Chemical Effects of the Voltaic Apparatus.

124. The first chemical effect produced by the pile, was the decomposition of water. This discovery is due to MM. Carlisle and Nicholson. If we adapt to the ends, which are commonly called the poles of the electromotive apparatus, platina wires leading into a glass vessel partly filled with water, we shall see a continued current of oxygen gas disengaging itself from the wire which communicates with the vitreous pole, and at the same time a current of hydrogen gas disengages itself from the other wire which communicates with the resinous pole. If instead of platina wires, we employ wires of copper, silver, or of any other metal which is easily oxidated, the hydrogen continues to appear at the resinous wire; the oxygen no longer disengages itself under the form of a gas, but combines with the wire and oxidates it. It is of no importance whether the pile be insulated or not.

To determine whether the two gases which are disengaged are really in the proportion which constitutes water, it is necessary to collect and measure them. The most convenient apparatus for this purpose is represented in figure 62. *EE* is a glass tunnel of which the mouth *BBB* is closed by a cork stopper, through which are made to pass two small hollow tubes of glass at the distance of about one third of an inch from each other, and of which the extremities, both within and without, extend a little beyond the two surfaces of the cork. Each tube serves as a case to a platina wire, which is cemented in it with sealing wax, so that the tubes are perfectly closed. The whole is arranged in such a way, that the two wires rise parallel to each other, in the interior of the tunnel, to the height of one or two inches above its bottom. We pour some water into the tunnel, and cover each wire with a small glass bell also filled with water. Finally, we make the external parts of the wires communicate, each with one pole of the pile, and the apparatus is complete. We suffer it to act for some time, after which we stop the action, and measure the volume of gas disengaged under each bell. We find twice as much hydrogen as oxygen in bulk. These are in fact the proportions which constitute water; for upon re-establishing the combination by means of the electric spark, and

the small apparatus above described, no gaseous residue remains. That we may lose nothing of the action of the pile, it is necessary that the communication of the wires with the extreme plates should be perfectly established. For this purpose, there is no method more convenient than to immerse them in a small glass vessel filled with mercury, in which are also placed two large iron wires connected with the extreme plates of the electromotive apparatus.

125. With this apparatus, MM. Gay-Lussac and Thénard observed that the quantity of gas disengaged in a given time by the same pile, whether constructed with pieces of cloth or in the form of troughs, varies considerably, according to the nature of the substances dissolved in the water with which the tunnel is filled. Concentrated saline solutions and mixtures of water and acid give most abundant and most rapid decompositions. The result diminishes according as the proportions of salt or acid are less; and finally, when the tunnel contains only boiled and perfectly pure water, scarcely any gas is disengaged. They supposed that the interposition of the water becomes a sufficient obstacle to prevent the circulation of the electric current from one pole of the pile to the other; for, if they introduce into the arc of communication the most delicate bodily organs, all the effects which the voltaic apparatus ordinarily produces cease, at least when the communication is established through the water itself. Thus pure water, which transmits a strong electricity, such, for instance, as is obtained from common machines, becomes almost a non-conductor for the feeble repulsive forces furnished by the voltaic apparatus. Hence they applied the general laws which had been discovered relative to imperfect conductors; that is, for a given distance of the wires, the insulation will be perfect only for a certain degree of repulsive force, determined by the number of plates of the apparatus; so also for each non-conducting support, the degree of repulsive force, where perfect insulation commences, is as the square roots of the lengths of the supports; so also for each electromotive apparatus, there must be a certain distance of the wires at which the communication will be entirely interrupted. They attempted to find the influence upon the insulation arising from the more or less extended contact taking place between the support and the insulated body; and they supposed that by shortening the wires beyond a certain limit, the quantities of

gas disengaged in the same fluid are considerably diminished; they are increased anew by substituting a liquid of a greater conducting power. This want of conducting power in the water may be immediately rendered sensible by a very simple experiment. Having insulated a pile and placed conducting wires at its two poles, immerse these wires in a glass vessel partly filled with common water; the gases will be immediately disengaged in abundance. If we withdraw one of these wires from the water, and taking it in one hand, immerse the other hand in the water of the vessel, we shall feel a shock as usual. But instead of this, make the communication by means of a column of water a fifth or a sixth of an inch in diameter, and an inch and a half or two inches in length, which may be done by drawing up the water of the vessel with a tube of these dimensions; then, although the most delicate organs are within the arc of communication, a feeble effect upon the taste, but not the slightest convulsion, will be perceived. Biot in this way arranged a pile of sixty-eight pairs of plates, the poles of which communicated by tubes that were not capillary, filled with distilled water, and about forty inches in length. The apparatus was in action for twenty-four hours, without disengaging a particle of gas; in endeavoring to make a communication from one pole of the pile to the other by means of the columns of water contained in the tubes, not the slightest sensation was felt, which the electromotive apparatus ordinarily produces. In fact, the whole took place as if an insulating body had been interposed between the two poles; but all the effects reappeared as soon as an immediate communication was made by the free surface of the water. On this account it is to be regretted that, in the experiments of MM. Gay-Lussac and Thénard with distilled water, they had not attempted to extend the wires over the surface of the water likewise; for Biot thinks that in this case, the communication between the two poles of the pile would have been established. The view which these eminent philosophers took of their own experiments was based upon a belief in the contact of different metals, as the sole electromotive power in the voltaic pile. The chemical theory of the pile, which is now generally received, would furnish another and a different explanation.

126. MM. Gay-Lussac and Thénard endeavored to ascertain whether there be not some ratio between the quantities of gas

disengaged by the pile and the quantities of salt thrown into the water of the tunnel; but they have no simple relation except for the sulphate of soda. The quantities of gas disengaged in a given time are very nearly proportional to the cube root of the quantities of salt dissolved in the water of the tunnel. The solution of nitre produces a contrary effect; being saturated with this salt, water yields less gas than when not saturated. But it is necessary to observe that the decomposition of the water is not the only phenomenon which takes place in these experiments. Most of the substances which are dissolved in this liquid, and subjected with it to the action of the electric current, suffer also changes in their constitution. We are not therefore to expect to find a constant or simple relation between the absolute energy of the apparatus and the mere disengagement of the gases.

The first example of this action of the pile upon the different substances contained in water was observed by Cruikshank in repeating the experiment of Nicholson and Carlisle. Having employed, as a conducting medium, water charged with acetate of lead, he saw that the resinous wire was covered with a multitude of small needles of metallic lead. He obtained analogous effects with solutions of sulphate of copper and of nitrate of silver. In the latter, the small needles of silver were articulated upon each other, like a species of vegetation, so as to form, by their union, what chemists call the tree of Diana. The electric current, therefore, disengaged the metals from their combination with the acids which held them in solution, and with the oxygen which is necessary to dissolve them, in the same way as, in the first experiment on water alone, it separated the hydrogen from the oxygen with which it was combined; and in both cases alike, the oxygen was developed at the vitreous pole, while the substances with which it was saturated, became free at the resinous pole.

127. In order to study the nature of the power which produces these decompositions, Cruikshank caused the voltaic current to pass through solutions charged with blue vegetable colors, which have the property of turning red by the contact of an acid, and green by that of an alkali. He observed that the first effect took place about the vitreous wire, and the second about the resinous wire. This experiment may be performed with ease and elegance in the following way, according to Singer. We bend a small tube of glass

into the form of the letter V, and introduce into each branch a platina wire which is made to communicate with the two poles of the voltaic pile. We then pour into the tube a solution of red cabbage, which is of a delicate blue color and very sensible to the action of acids and alkalis.* The decomposition of the water immediately begins to take place as usual, and the two gases which constitute it are disengaged; but besides this, after a short time, we shall see the liquor become red about the vitreous wire, and green about the resinous wire. When this effect has become very evident, invert the communications of the two wires, by changing the poles to which they are applied, and suffer the apparatus to act anew. The red will soon disappear from one side, and the green from the other; the liquor will become blue again in the two branches; and after a time, each color will be found to be replaced by its opposite. When these phenomena were first observed, it was inferred that the electric power actually formed an acid about the vitreous wire, and an alkali about the resinous wire, but farther researches, which were principally those of Sir Humphrey Davy, have shown that these phenomena were simply the result of decompositions produced by the electric current in the media through which it is made to pass. This able chemist found that, in order to prevent them, it was necessary to employ every possible precaution. For instance, he still obtained signs of alkali and acid, when he made the voltaic current pass for some time through perfectly pure water, contained in different glass vessels communicating only by indissoluble fibrous substances, such as films of amianthus, or of asbestos, saturated with water. In this case, the alkali is obtained

* The following is the method recommended by Mr. Singer for preparing the solution. When we wish to obtain a very sensible reagent, we infuse for a few moments thin leaves of red cabbage in a quantity of warm water just sufficient to cover them. This water takes a beautiful blue color, which the contact of acids changes to red, and that of alkalis to green. The solution can be preserved but for a very short time without undergoing a change. We obtain a more durable reagent, but one which is somewhat less delicate, by adding several drops of sulphuric acid for every pint of water which is employed in forming the infusion. In this case the color of the infusion is red; and when we wish to make use of it, we take a small quantity and neutralize it by the application of a few drops of ammonia until the blue color re-appears; but the difficulty of obtaining the precise point of neutrality must render this preparation less sensible than the first.

from a partial decomposition of the glass itself; the acid is formed by the oxygen disengaged from the water, which, being in the nascent state, combines with the nitrogen of the surrounding atmosphere, and constitutes nitric acid. These traces of nitric acid were still sensible, although very weak, when common distilled water was used, placed in gold cups; but it was found also that such water was not perfectly freed from every foreign substance. Finally, the attempt succeeded by employing water distilled very gradually in alembics of silver, and exposing it to the electric current in vessels of gold. All traces of alkali and acid now entirely disappeared.

128. This inquiry, while it proved the great power of the voltaic apparatus as an instrument of chemical decomposition, showed also the necessity of guarding against the effects of its action upon the vessels themselves containing the solutions which were to be subjected to trial. The experiments, which required much exactness, it was necessary to perform in cups of gold or agate withdrawn from the contact of the air. The solutions which it was proposed to try, were put into different cups, and a communication was established between them by means of films of amianthus. But new and unexpected phenomena were now presented. Substances, which were at first mingled, and distributed uniformly through the conducting medium, separated under the influence of the voltaic current, and each of them was found collected in one cup, apart from the other. Others which had been at first placed in different cups, were found to have changed places; so that it was necessary to recognise in this current a particular power of transfer, which collected in general the acid principles at the vitreous pole, and the salifiable bases at the resinous pole. This beautiful discovery was made by two Swedish chemists, Berzelius and Hisinger.

Let us suppose, for instance, that we employ but two cups, and that we fill them both with a solution of sulphate of soda. After an action of some hours, all the salt is found to be decomposed; the cup which communicates with the vitreous pole contains a solution of sulphuric acid, and we find that the soda is in the cup which communicates with the resinous pole. It is necessary, therefore, for this effect to take place, that the alkali and the acid should have entirely passed from one cup to the other along the films of amian-

thus; or rather along the particles of water which moisten these films.

129. This experiment may be varied by employing three communicating cups, of which the two extreme ones contain only distilled water charged with the blue infusion of red cabbage, while that in the middle contains a solution of sulphate of potash. We place the two extreme cups in communication with the two poles of a voltaic pile; after some time we find the salt of the middle cup decomposed, and its separate elements transferred into the two others. The acid passes to the cup which communicates with the vitreous pole, and reddens the blue liquor contained in it, while the alkali goes to the liquor which communicates with the resinous pole, and changes it to green.

130. A very remarkable circumstance in this transfer is, that the substances transferred are always carried through media for which, in their ordinary state, they have a very strong affinity, yet without combining with them permanently in their passage. The following is one example among many others of this fact. We employ three communicating cups; the first, in which the resinous wire is immersed, contains a solution of sulphate of potash; in the second, we place a solution of ammonia, a substance having a very great affinity for sulphuric acid. The third, in which the vitreous wire terminates, contains only pure water. When the pile begins to act, the electric current decomposes the sulphate, retains the potash in the first cup, and transfers the acid into the third, where it is found free, although to arrive there, it must have passed through the ammoniacal solution. If instead of the ammonia we substitute an acid, and immerse the vitreous wire in the solution of the sulphate of potash, it is the potash which is transferred, and it goes into the cup containing the resinous wire; and this it does by passing through the intermediate acid, without being retained by its affinity for that substance. And not only do the products transferred thus resist very powerful affinities, but the most sensible reagents appear not to be affected by their passage, and give no indication of it. Let us suppose, for instance, that we employ, as before, three communicating vessels, two of which, namely, that in the centre, and that which the vitreous wire enters, contain a neutralized infusion of red cabbage, while we put a solution of sulphate

of potash into the third which receives the resinous wire. After having made the vessels to communicate by moistened films of amianthus, or of cotton, if we cause the voltaic current to act upon the liquors which they contain, the sulphate will be decomposed, and the acid will pass into the liquor of the vitreous vessel, which it will redden, without altering in any way the color of the intermediate solution which it must nevertheless have passed through. If we invert the communications of the extreme vessels with the pile, the transferred potash will present an analogous effect. It seems, therefore, that the electricity attaching itself, as it were, to the particles which it transfers, modifies the natural affinities, and modifies them differently according to their nature. This result is the more surprising, since, when we examine the mode of distribution of the electricity among bodies of a sensible magnitude, we find that it diffuses itself over them in proportions depending upon their form simply, without manifesting any particular affinity for the matter which composes them.

All the oxides and the acids which contain oxygen, have been decomposed by the voltaic current, and the principle which is united with the oxygen, is transferred to the resinous pole; and the oxygen, according to its constant disposition, goes to the vitreous pole. These interesting facts were first made known, as I have already said, by MM. Hisinger and Berzelius. Sir Humphrey Davy, in varying and extending them, was led to try the action of the voltaic apparatus upon the alkalis, which had till that time been regarded as simple substances. He perceived what the philosophers of Europe have since witnessed with surprise and admiration, that bubbles of oxygen were disengaged at the vitreous pole; while there appeared at the resinous pole a number of brilliant globules of a metallic aspect and yet very light, which burned briskly in the air, and even possessed the singular property of becoming inflamed in water. These were, therefore, the metallic bases of soda and potash, which were afterwards called *sodium* and *potassium*. But from the very nature of their properties, only minute portions of these substances could be obtained, which were destroyed in the air as fast as they were formed. It was therefore necessary to seek for some means of preserving them from the contact of the air which consumed them. Dr. Seebeck invented a very simple process for

this purpose, which consists in combining sodium and potassium with mercury as fast as it is disengaged. We make a hole in a small fragment of the hydrate of soda or of potash, which is then filled with mercury; we place this fragment on a metallic plate, and immerse in the mercury the resinous wire of a voltaic apparatus, consisting of at least two hundred pairs of plates. We make the other wire communicate with the metal support; and the soda or potash is decomposed, as well as the water which it contains. The oxygen of both one and the other go to the vitreous pole, whither their electric state draws them. The hydrogen and the sodium or potassium thus abandoned go to the resinous pole, where the hydrogen is disengaged in the form of a gas, and the potassium or sodium combines with the mercury which thus preserves it from the action of the air. From time to time we pour the amalgam into the oil of naphtha, and renew the mercury. When we have collected a certain quantity of amalgam, we distil it in a retort, with the least possible quantity of air. The oil is evaporated first, and then the mercury, and at length the sodium or potassium remains free. In order that the decomposition of the potash may take place by the process which we have now described, it is necessary that these alkalis should contain a sufficient quantity of water to transmit the electricity of the pile, yet not so great a quantity that its decomposition shall require the action of all the electricity transmitted, for then the potash and the soda will not be decomposed. Sir Humphrey Davy and Dr. Seebeck, by similar processes, were able to discover in the other alkalis the clearest evidence of decomposition. But it does not belong to a treatise like the present to enter into minute details upon such a subject; I shall only add, that soon after the first discovery of Sir H. Davy respecting the composition of potash and soda, MM. Gay-Lussac and Thénard succeeded in depriving these substances of their oxygen, by the simple action of chemical affinities.

131. We have thus far considered the action of the pile only as decomposing bodies; but it produces other very remarkable effects. For instance, if we make the communication between the two poles by very fine wires, and gradually bring them towards each other till they come in contact, an attraction takes place between them, which holds them together in spite of their elasticity; the wires being of iron, a visible spark takes place between them,

which, as we shall presently see, produces a real combustion of the iron. This phenomenon succeeds more certainly, when we arm the extremity of one of the wires with a strip of gold leaf. This leaf is consumed at the point where the spark is seen. We may inflame detonating gases with this spark, and even phosphorus and sulphur, as with the spark drawn from our common electrical machines.

We are speaking only of the effects produced by piles, of which the discs are a little larger than a dollar. But these effects, it is evident, will become much greater if we employ the same number of plates of a larger surface. For in piles in which the number of the elements and the nature of the moist conductors are the same, the thickness of the free electric stratum, upon plates of the same rank, is also the same, as we learn both from theory and experiment; whence it follows that the whole quantity of electricity which these piles possess in a state of equilibrium, is exactly proportional to the surfaces of the plates; and the same proportion also exists in a state of action, at least if we suppose that the conducting power of the interposed liquid is the same, and that this liquid as well as the surfaces of the plates, undergoes, in the course of the experiment, only similar alterations. Thus MM. Gay-Lussac and Thénard found that the quantity of gas, disengaged in a given time, is proportional to the surface of the plates, or, which is the same thing, to the whole quantity of electricity. The same proportion is observed in all other chemical effects. A pile with large plates, although composed of a small number of pairs, will ignite a certain length of iron wire. This phenomenon was observed for the first time by MM. Hachette and Thénard. The English philosophers, by giving to the voltaic apparatus a better form, and uniting with the size of the plates the increase of force which results from their number, have carried this effect to the highest degree. With their improvements, long wires of iron, of platina and other metals, are heated not only to redness, but until they are fused and resolved into globules; and if they are made to pass during part of their course through liquids, these liquids may be heated to boiling. If instead of wires, we employ leaves beaten or rolled thin, they inflame and burn with different colors according to their nature. The sparks which are excited between the leaves or conducting wires,

when they are brought nearly into contact, are so powerful as to become visible even in water. But nothing is more remarkable than the phenomenon exhibited when the conducting wires are terminated by points of perfectly dry charcoal. The great apparatus of the Royal Institution of London, which is composed of two thousand pairs of plates, four inches square, being prepared in this way, the spark began to dart from one charcoal point to the other, when they were at the distance of about $\frac{1}{15}$ of an inch. But soon after, the two points being brought to a state of high ignition, they might be removed from each other to the distance of four inches, without interrupting the light. The constancy of the electric discharges, between the two points, formed a continued jet of light bent in the form of an arc, of a splendor superior to any other flame, attended with so intense a heat, that the most refractory substances were fused, and globules of diamond and of plumbago disappeared as if they had suddenly evaporated. These effects were produced in the same way, and with still more energy, when the charcoal points were placed in air rarefied by the air pump. In this case, the stream of light continued to flow from one point to the other when the distance was no less than six inches; and it might be continued whole hours without the charcoal being sensibly diminished. Hence it has been inferred with some probability, that the electric light is produced in this case, as it is in ordinary electric explosions, by the passage of the electricity through the air, or the rarefied vapors which separate the two points. The first discharge from one point to the other, must pierce this stratum of air or vapor, and for this reason it takes place only at a small distance; but when it has once effected a passage, and divided, by its repulsive force, the particles of the surrounding medium, the following discharges, which meet with little interruption, tending all in the same direction, easily make their way through the rarefied air, or through perhaps an almost perfect vacuum, which they have only to maintain, and they therefore take place at a greater distance.

132. This continued production of light, and the analogous disengagement of light and heat which is observed in the wires when they are traversed by the voltaic current, are very remarkable phenomena; and the more so because, in the case of the wires, when they are placed in a vacuum or in gases with which they cannot

enter into combination, the ignition may be supported for whole hours, and be renewed as often as we choose, without any diminution of their weight. It is extremely difficult, not to say impossible, to conjecture whence is derived the light and heat thus produced. Will it be said that the light is disengaged by the compression which the electric current causes the substances upon which it acts to undergo? But then, since the current is continuous, it would seem that the compression, being once exerted, ought to continue during the whole time of the experiment; and thus we could at most attribute to it the first appearance of the light, but not its continued production. Can it be, that the two electric principles, in combining with each other, produce light immediately? We are not acquainted with any phenomenon which would oblige us to regard this supposition as impossible, or even as improbable. The following experiment tends to confirm it. When a voltaic trough is charged with a saline solution or with an acid diluted with water, we observe that its chemical action is immediately at its highest point of energy, and that in a few instants it rapidly decreases, so as to become, after some hours, very feeble, or nearly insensible. We shall soon see the cause of this decrease; it is here stated simply as a fact. Now if, at the moment of the most powerful action of the apparatus, we interpose between its poles the longest iron wire of a given diameter which it is capable of heating to redness, we shall soon find that it is no longer sufficient to heat a wire of the same length, and that it goes on diminishing until an iron wire, however short, will discharge the apparatus completely without any appearance of ignition. Let us now suppose, that, instead of shortening successively in this way the interposed wire, we keep it always of the same length, we shall find that the continually decreasing portion which suffers ignition, is situated at the middle of the wire; so that at the moment of the last possible ignition, it will be found to take place precisely at the middle of the conducting wire, where in fact it appears that the union of the two electric principles must be most abundant.

133. In all which precedes, we have supposed the apparatus to consist of a considerable number of plates; but the ignition may be produced with a single pair by rendering the thickness and the length of the wire very small compared with the extent of surface belonging to this pair of plates. For instance, we take a rectangu-

lar plate of zinc ZZ, about two inches in breadth, by six in length. We wrap about it a plate of copper CC, from which we separate it by rolls of resin, in such a way that the zinc shall not touch the copper at any point. The zinc plate has on one of its sides, an appendage, m, of the same metal, to which is fixed a copper rod t, directed parallel to the length of the plate; another copper rod t', fixed to the exterior surface of the copper plate, rises in a direction perpendicular to the rod t, so that the extremities of the two rods are about a fourth of an inch distant from each other. We join these extremities by a platina wire f, of the same length and of about one four-thousandth of an inch in diameter. This system evidently forms a voltaic pair, one of the elements of which is the zinc plate, and the other is the system of the copper rod t, of the platina wire f, of the rod t', and finally, the large copper plate CC. The development of electricity is produced by the contact of the rod t, with the appendage m. Now suppose the whole apparatus suspended by a non-conducting rod attached to this appendage; the zinc and the copper have no communication with each other, except by the surface in contact at $m\ t$; consequently there will be no circulation of the electricity. But this circulation will be possible if we interpose between the large plates C, Z, some moist conductor, as a saline solution, or what is still better, a mixture of one part by bulk of nitric acid, one of sulphuric acid, and fifty or sixty of water. Indeed, when we immerse a portion of the surface of the large plates in such a mixture, we perceive a lively effervescence to take place immediately in the conducting liquid; and in a few moments, the platina wire interposed between the rods $t\ t'$, is heated to redness. This state of ignition continues for a long time, especially if we give the conducting liquid free access to the zinc plate, by making openings O, O', O'', in the lower part of the copper plate; and when it has ceased, it may be made to re-appear, by substituting fresh liquid for that which has been used. Besides, it will be readily perceived, that the dimensions here attributed to the combined plates, are not absolute, but merely relative to the diameter and length of the wire to be ignited. By greatly diminishing its length and diameter, the wire might be heated to redness with a pair of plates of much smaller size. Dr. Wollaston has carried this to the extreme by employing as a conductor an exceedingly fine platina wire, when very small copper and zinc plates are sufficient

Fig. 64.

to form the apparatus; and upon being immersed in an acid mixture, the wire, which was at first almost invisible on account of its fineness, becomes manifest by its ignition. This experiment presents in its details, some particulars which it is hard to reconcile with the idea, that the development of electricity which takes place results from the simple contact of the metals.

Examination of the Changes which take Place in the Voltaic Apparatus by its Action upon itself.

134. The chemical action of the voltaic apparatus is not exerted at the extremities merely of the wires, by which the communication is established between its two poles; it occurs also between its metallic elements, the moist conductor which separates them taking the place of the liquid in which the wires are immersed. Hence result, in the very interior of the apparatus, considerable changes which affect its electrical state, either by changing the conditions of equilibrium in the contact of the elements of the pile, or by altering the conducting power.

The first effect of this action, is a rapid absorption of the oxygen of the air which surrounds the apparatus. We may ascertain this in a very simple way, by placing a vertical pile upon a support surrounded with water, and covering it with a receiver, the base of which descends into the water. In a few moments, the water is seen to rise in the interior of the receiver, especially if we establish a communication between the two poles of the pile by wires, so as to cause the circulation of the electricity through it. When there is no communication established, an absorption still takes place, but much more gradually. In all cases, after a certain time, depending on the size of the pile, and the quantity of the surrounding air, the absorption ceases, and the air which remains under the receiver no longer presents any traces of oxygen. This phenomenon was discovered by M. Frederick Cuvier and Biot, soon after the voltaic apparatus became known in France. It was attended with a circumstance worthy of note; namely, that as long as there remained any oxygen to be absorbed, the chemical and physiological effects of the apparatus still continued, although with decreasing intensity; so that if the conducting wires attached to the two poles be made

to return from under the receiver, in tubes of glass, they may be used to decompose water and communicate shocks to the organs. But all these effects cease, when the surrounding oxygen is exhausted. By a natural consequence, the chemical and physiological action of the same pile is much more lively and more durable when it is surrounded with pure oxygen, than when it is enclosed with an equal bulk of common air; and even in the latter case, when by the progress of the absorption, the pile is found immersed in an atmosphere of nitrogen, and has become entirely extinct, the introduction of a small quantity of oxygen is sufficient to restore it.

135. When we disconnect the pile which has thus been kept in action for several days, under a receiver filled with atmospheric air or oxygen, with a communication constantly established between the poles, we find that the metallic discs which compose it adhere to one another and to the intermediate pieces of cloth with such force, that it requires some effort to separate them. When detached, we perceive that the chemical action of the pile, has reacted upon itself, and has produced remarkable changes in its own elements. If the pile were composed in this way, zinc, moisture, copper, zinc, &c., and placed upon its zinc base, we constantly find that parti- Fig. 66.
cles of each piece of zinc have been detached, and transferred to the copper of the pair next above; and if the copper and zinc elements of each pair are simply placed the one upon the other, so that they may be separated, we also find that particles of the copper of each pair have gone to the piece of zinc next above. If this arrangement of the pile is inverted, the order being copper, moisture, zinc, copper, &c., the copper descends upon the zinc beneath, Fig. 67.
and the zinc upon the copper, from the top to the bottom of the column. The direction of the *transfer* is inverted with respect to a perpendicular; but it remains the same as to the order of the elements of which the apparatus is composed.

According to this arrangement, it is necessary that the zinc in order to reach the copper should traverse the piece of moist cloth which separates them. In piles, where the communication has not been established, this transmission does not take place, the surface of the copper is smooth, and that of the zinc which is opposed to it is only covered with small black threads, which follow the direction of the threads of the cloth. When the communication has been established a short time, particles of oxide begin to pass, and go to

the copper. Finally, if the action is strong, the surface of the copper becomes entirely covered. Then the chemical and physiological action of the pile ceases, either because the oxide of zinc, deposited upon one of the faces of the copper, and the metallic zinc which touches the other face, exert the same electrical influence in the contact; or because the interposition of this layer of oxide presents too great an obstacle to the transmission of the electricity, or more probably from these two effects combined.

Sometimes the oxide of zinc, after having traversed the piece of cloth, returns to the metallic state upon the copper. Then the parts of the piece of copper upon which this precipitation takes place are in contact with zinc at both surfaces. The inequality of the electric state at those surfaces ceases, therefore, with respect to these parts, and they no longer act in the pile except as neutral conductors; and this prevents the parts of the same piece of copper, which the zinc, thus transferred, has not entirely covered, from preserving with the piece of zinc which touches them at the other face, the general relations of electric equilibrium which take place in contact, and from thus developing the same quantities of electricity as before.

The motion of transfer being from the zinc to the copper through the moist conductors, when the copper tends to the zinc, it is always where the faces touch each other immediately. Then if the copper adheres to the zinc, and preserves its metallic brilliancy, brass is sometimes formed. These precipitations take place only when the communication is established between the extremities of the pile. It is also necessary, in order that they may occur, that the cloth discs should not be too thick, nor of too close a texture.

136. These were the first phenomena of transfer which were observed with the voltaic apparatus. M. F. Cuvier and Biot announced them in the Journal de Physique. Their theory is the same as that of the other chemical decompositions which take place between the poles of the pile. Of course, when the battery is in very intense operation, the interior action becomes proportionally strong, and the energy of the apparatus rapidly diminishes. After the plates have been incrusted in the way described, it is necessary that the apparatus should be separated and the plates cleaned before the action can be renewed. This is a serious inconvenience in the electric column of Volta. But in the form which the battery soon assumed

in England and America, and which is now universally adopted, it is only necessary to turn the liquid off, wipe the plates, and then immerse them again.

Mr. Spencer has recently made a beautiful application of this wasting process of the voltaic battery to the purposes of reproduction in the arts. If the two wires which come from the two extremities of the voltaic apparatus are brought near together in a solution of sulphate of copper, the solution will be decomposed according to the laws of electro-chemical action; the copper will go to the negative pole, the acid will attack the positive pole. If a plate of copper or other metal form the termination of the negative extremity of the battery, the disintegrated particles of copper will be deposited in minute atoms upon the plate; and if the plate be engraved a beautiful reverse copy will be formed. A more simple method would be to make the plate to be copied an element of the pile itself, and act upon it by the chemical and electrical action that is going on in the interior of the apparatus. Thus, let *A* represent a glass or tumbler containing the copper solution. *B* is a gas glass, having one end closed with brown paper or plaster of Paris, and containing a saline solution. *C* the plate or medal, required to be copied, has a wire attached to it, the other end of which is fixed to a piece of zinc or other metal which bears the proper electrical relation to the metal of the first plate. The wire is then bent into the form it has taken in the Figure. *D* is a wooden cover into which the gas glass fits. A slow communication takes place between the two plates, which make the positive and negative elements of the pair, by means of the two solutions, and the pores of the paper or plaster bottom of the gas glass. The deposition of the copper is now made upon the interior plate *C*, as it was before in that part of the circuit outside of the apparatus. Such is the general nature of the electrotype process, as it has been called, though in practice the details require particular attention. It promises wonderful facilities for multiplying works of art in metal, by voltaic electricity, and has already been applied with partial success to copying Daguerreotype plates.

137. Having considered the various forms which the voltaic apparatus assumes, and the chemical changes which it produces on itself and on foreign bodies, subjected to its influence, we are now prepared to consider the theory of the new electricity, and the theory of

electro-chemical decomposition. A satisfactory view of this complex subject would require a long discussion, inconsistent with the limits of such a work. We must refer those who desire to become acquainted with the latest developments of electro-chemical science to the successive series of papers, published by Faraday in the Transactions of the Royal Society. It may be well, however, to notice here a few points which have been cleared up by recent experimental inquiries. Formerly, the energy of the battery was supposed to reside chiefly at the opposite extremities which were called poles. It appears now that when the circuit is completed, every part of it is equally active; the general electrical equilibrium has been disturbed, and this derangement is felt equally through the whole length of the communication. If we introduce a compound substance at any point, or at several points at once, an equal amount of chemical decomposition will take place. No greater effect can be produced outside of the battery than within the battery. The chemical change which the elements of the battery experience, sets free an equivalent force which appears in the form of electricity, and is competent to produce a corresponding change at any other point, so that the amount of chemical decomposition may be considered as an exact measure of the electricity disengaged at any time, and upon this principle a voltameter has been devised. It would seem from this statement that no more electricity is set in motion with a large number of plates than with a single pair. This is true in all cases. The *quantity* of electricity depends upon the size of the plates alone. The number of plates adds to the *intensity* of the current. It is not of much importance how we conceive of this. In our ignorance of the nature of electricity, it is not probable that we shall understand completely the modus operandi. We may suppose, however, that in a large number of pairs, connected together by good conducting surfaces, the chemical decomposition and recomposition acquire a momentum, so to speak, and are thus capable of producing effects which would be impossible to the same amount of electricity in a low state of tension. Whatever be the origin of the difference, we are now accustomed to admit, in effect at least, this distinction of quantity and intensity.

MAGNETISM.

General Phenomena of Magnetic Attraction and Repulsion.

138. Most of the fragments of iron ore in which a degree of oxidation has taken place, are found to possess, when taken from the earth, the singular property of attracting iron, by an invisible power. This attraction is often so feeble that it is necessary to employ the most delicate processes in order to render it sensible; but it is sometimes strong enough to support considerable weights. The mineral is then called a *magnet*† from the Greek word μαγνης; and hence the term magnetism is used to stand for the phenomena of attraction exhibited by this mineral.

139. The most simple method of showing the power and distribution of magnetism in a piece of natural loadstone, is to roll it in iron filings, and afterwards to withdraw it from them. It will then be seen that different quantities of these filings will be attached to different parts of its surface. This effect is particularly sensible in two opposite points, *N*, *S*, where the filings are accumulated in the greatest abundance, standing as it were on end nearly parallel to each other. These parts are called the poles of the magnet. In order to observe their properties more easily, we shall suppose that the loadstone is cut by two plane and parallel faces, *A*, *B*, in a direction nearly perpendicular to that of the small filings. The following phenomena will then be observed.

Fig. 76.

Fig 77.

* The name *loadstone* is also applied to it, from the Saxon word *lædan*, to guide.

Each of the poles, presented to the iron filings, will attract them *at a distance*, in the same manner that a stick of sealing wax, when rubbed, attracts all bodies that are presented to it. If we suspend horizontally a small needle of iron or steel, by an untwisted linen thread or fibre of silk, or any other sufficiently flexible substance that will allow it to move with full liberty, each pole of the loadstone will attract it, and cause it to oscillate about its centre. This power is exerted with equal force through both conductors and non-conductors of electricity. Its action is not intercepted by water, glass, paper, or flame; insulation is unnecessary, and the loadstone loses nothing of its virtue by being touched.

Of the nature of the principle which produces these phenomena, we are entirely ignorant; but to avoid circumlocution, we shall designate it by the name of *magnetism*, in the same way that we give the name of *electricity* to the unknown principle of electrical phenomena, and the name of *caloric* to the equally unknown principle of heat. It is necessary, in order to proceed philosophically, to attribute to this unknown principle only the properties and qualities which are indicated, or rather which are rendered necessary by the phenomena which it produces.

140. If we place the polar surface A, of one loadstone, successively in contact with the surfaces A' and B' of another, we shall find that it attracts one of them, B', for example, and repels, A'; and reciprocally, the polar surface B of the first loadstone attracts A' and repels B'. The mutual tendency of the attracting faces shows itself, not only by their adherence when they touch each other, but also by the effort exerted when they approach near each other. The repulsion is not so easily recognised in this manner; but we may render it sensible, by placing one of the loadstones on a piece of cork floating upon water; for, as it is then at liberty to move, if we present to it the other loadstone it will approach to it or recede from it, according as it is attracted or repelled.

We see, therefore, from this experiment, that the powers exerted by the two polar surfaces of a loadstone are not similar, since the one attracts what the other repels, and *vice versâ*. The most simple way of expressing this result, will be to distinguish magnetism into two kinds, differing, if not in their physical essence, at least in the external and apparent mode of their action. It is

thus that electrical attraction and repulsion lead us to distinguish electricity into two kinds, namely, the vitreous and the resinous, which have received these names from the substances in which they are developed; and it is of importance to remark, that the two magnetisms reside in the opposite poles of a loadstone, in the same manner as the two electricities reside in the opposite poles of a heated tourmaline.

141. If we examine the crest of filings attached to the poles of a loadstone, we shall observe that their radii are composed of several parcels of filings, adhering end to end to one another. This phenomenon is particularly deserving of attention, as it teaches us that iron placed in contact with a loadstone, becomes itself magnetic, in the same manner that an insulated body becomes electrical when placed near another body that is electrified.

In order to establish this property, we take several bars of soft or malleable iron, such as is used for keys. After we are satisfied that none of these bars possesses any perceptible magnetism, which may be determined by their not attracting iron filings, we suspend one of them *a b* to one of the poles *B* of a loadstone; the lower Fig. 78. end *b* of this bar will immediately acquire all the magnetic properties. If we now place it among iron filings, they will adhere to it, and we may even suspend to it a second bar *a′ b′*, and to this a third bar *a″ b″*, as represented in the figure. All these will adhere to one another, till their total weight exceeds that which the loadstone is capable of supporting. As soon as the first bar *a b* detaches itself they will all separate and fall; and if we again try to unite them, they will be found no longer capable of supporting each other. They preserve, however, in general, some feeble remains of magnetism which will become sensible by placing them in filings of iron, or presenting them to iron needles freely suspended. This transient communication of magnetism will still take place, even if the first bar, without touching the loadstone, is kept at a distance from it by the interposition of a piece of card, or a plate of glass; but the total weight thus supported at a distance is much less, and the magnetic attraction decreases very fast as the distance increases.

142. If instead of soft iron, we employ bars of steel, or iron hardened by the hammer, the adherence of these bars to one another is less easily and less readily effected, but it is more durable; and the

bars when separated from the loadstone, preserve the magnetism which they have acquired from being in contact either with one another or with the magnet. The soft iron and the steel employed in these experiments have the same relation to each other as a rod of metal, and a stick of sealing-wax, when submitted to the influence of an electric body. In the metal the decomposition of the natural electricities is sudden, but the recomposition is equally so, and it takes place as soon as the metal is withdrawn from the influence of the electrified body. In the wax, on the contrary, the natural electricities are separated with difficulty, but when the separation is effected, they experience the same difficulty in their reunion, and the electric state continues after the action of the electrified body has ceased.

Magnetism may be communicated to a bar of steel in a more prompt and energetic manner by two loadstones than by one, the two extremities being placed in contact at the same time with opposite poles. The same loadstone may thus successively render magnetic any number of bars, without losing any portion of its original virtue, from which it follows that it communicates nothing to the bars, but only developes by its influence some hidden principle. In the same manner a stick of sealing wax, when rubbed, loses nothing of its electricity by the decomposition which its influence effects at a distance in the natural electricities of other bodies.

143. If, after having magnetised in this way a steel bar or wire, we suspend it horizontally by an untwisted thread or bundle of silk fibres, or make it float on water by placing it on a small piece of wood or cork, it will not turn indifferently to every point of space, but it will take a determinate direction, which in this place is nearly north-northwest and south-southeast. We say in this place, for in certain parts of the earth, the north extremity of the bar deviates from the meridian towards the west; in others towards the east; while there are some in which it coincides with the meridian itself. This deviation is called the *declination of the magnetic needle* or the *variation*. It is constant at the same moment in every place; and all magnetic wires thus suspended freely will take directions truly parallel; but this common direction varies with the time, according to laws derived from observation. The vertical plane in which the magnetic needle directs itself at any given place is called

the *magnetic meridian*, because it does not deviate much from the astronomical meridian, in those parts of the globe which were formerly most frequently visited; but it is now found that in certain places, particularly in the polar regions, the declination of the needle becomes very considerable, and reaches even to 90°; so that the needle directs itself towards the true east and west, instead of turning to the north and south.

144. When several magnetic needles are thus freely suspended in a horizontal position, such of their extremities as turn to the same terrestrial pole are those which, in the magnetising process, have been in contact with the same pole of the magnet, and which have consequently received a magnetism of the same kind. If these extremities are made to approach, they will mutually repel each other; while, on the contrary, if the extremities which have received different kinds of magnetism are made to approach, they will mutually attract each other. In this respect, the two kinds of magnetism have the same effects as the two kinds of electricity.

When we hold one of the poles of a loadstone at a distance from a magnetic needle, suspended horizontally by its centre, the two poles of the loadstone act at once upon the needle; but the action of the nearest pole is always the strongest. The needle then turns towards the loadstone the pole which is attracted, and keeps at a distance the one which is repelled. If after it has taken a position of equilibrium, we turn it ever so little from its position, it will return to it by a series of oscillations, in the same manner as a pendulum drawn from a vertical line will return by the influence of gravity. A motion absolutely similar to this is observed in magnetic needles freely suspended, when they are drawn ever so little out of the magnetic meridian. From this circumstance, therefore, as well as from the constant direction which they take, we infer that they are acted upon by the terrestrial globe as by a true magnet; whether this property is owing to the number of mines of iron and magnetic substances contained in the earth, or whether it depends upon some other cause still more general. Hence we are furnished with convenient names for the two kinds of magnetism, the one being called *boreal*, which resides in the northern part of the globe, and the other *austral*, which resides in the southern; and therefore, in order to preserve the analogies of attraction and repulsion, we

must consider the extremities of the bars or needles which point to the north, as south poles, and the extremities which point to the south, as north poles.

145. The preceding experiments clearly indicate the direction of the vertical plane in which the resultant of all the magnetic forces is exerted at any particular place; but it still remains for us to determine the absolute direction of this resultant in the plane
Fig. 79. itself. In order to this, take a cylindrical needle of steel *a b*, provided with an axis passing perpendicularly through its middle point. When the needle is suspended by its centre upon well-polished planes, and accurately balanced so as to remain in any position indifferently in which it is placed, let it be carefully magnetized. Then upon being placed upon its supports in the magnetic meridian, it will no longer remain indifferent with respect to its position as before, but one of its poles, namely, that which possesses austral magnetism, will incline itself to the horizon, at least here; and after a few oscillations it will settle at a determinate angle. This angle is called the *magnetic inclination*, or the *dip of the needle;* and it is different in different places. Near the terrestrial equator, there is a zone where the needle placed in the magnetic meridian is horizontal. To the south of this zone, the extremity which possesses the boreal magnetism inclines downwards; to the north, that which possesses the austral magnetism; and this indicates two kinds of forces, the one austral and the other boreal, which are predominant on different sides of the equator.

In order to measure accurately the magnetic inclination, the axis of suspension of the needle is placed on the centre of a verticle
Fig. 80. circle of copper *MM* whose limb, divided into degrees, moves upon a vertical axis *VV*, so that it may be brought into every possible azimuth. The axis *VV* itself is placed in the centre of a horizontal circle, divided in a similar manner, which serves to determine the direction in which we turn the first circle *MM*. This apparatus is called a *dipping needle*. We shall soon point out the precautions to be observed in magnetizing and suspending the needle, and also in measuring its inclination; but this cannot be understood till the laws of magnetism are established.

When the direction of the resultant of the magnetic forces exerted by the terrestrial globe is thus ascertained in any particular place,

its action may be instantaneously exhibited by a very striking experiment. Suspend a magnetic needle *a b* by its centre, with a number of untwisted fibres of silk, placing it in a small paper box Fig. 81. and balancing it by a small weight on the south branch, so that it may have perfect liberty to move in a horizontal plane. Now, since the needle will naturally be in the magnetic meridian, and will lie there in a state of rest, take a bar *AB* of soft unmagnetized iron about five feet long and four-tenths of an inch square, and, inclining it nearly in the direction of the magnetic inclination, hold its lower end *A* near the northern extremity of the needle, and a repulsion will immediately take place. If, on the contrary, the upper end *B* of the bar is held to the northern end of the needle, by making the bar descend parallel to itself, as in figure 82, an attraction will take place. Hence it is obvious, that in this inclined position, the bar of iron is suddenly magnetized by the magnetic influence of the globe, in the same manner as it would have been by the influence of any other loadstone that might be presented to it; the lowest half of the bar nearest the earth acquiring a magnetism contrary to that which prevails in our hemisphere, namely, austral, and the upper half acquiring the opposite kind, namely, boreal magnetism. The two ends *A*, *B*, of the bar are therefore in the same state as the two ends *a*, *b*, of the needle, which were directed towards the same terrestrial poles, and it is from this cause that there is a repulsion when *a* and *A* are held near one another, and an attraction when *a* and *B* are brought together. In order to show that these phenomena really depend on the sudden communication of magnetism to the bar, in consequence of the position in which it is held, we have only to reverse the two ends, while its inclination remains the same. In this case, the under and upper ends of the bar will exhibit the same phenomena that have been already described; and therefore the phenomena will be opposite to those which the same end of the bar manifested before. The magnetic poles of the bar are then suddenly interchanged by being reversed; and it is in order that this may be effected instantaneously, that we have employed a bar of soft iron, and not a bar of steel or hard iron.

To this same cause is to be attributed the magnetism which the iron crosses of spires, and other bars of this metal, acquire, by being

kept a long time in a vertical position. The terrestrial globe magnetizes them also by its influence. The effect would be transient, if the iron which composes these bars were quite soft; but the hammering necessary to give them their shape, and even the action of the air, continued for a long time, communicates, particularly to the parts near the surface, a considerable degree of hardness. The magnetism in this case is not impressed instantaneously; time is necessary for its development by the action of the globe; but, for the same reason, the magnetism is permanent when it is once produced. According to Gilbert,* this remark was first made upon the bar of the weather-cock on the church of the Augustines, at Mantua. Others attribute the first observation of the fact in question to Gassendi, who noticed it on the cross of the church of Aix, in Provence; but, with regard to the theory of the phenomenon, which is the most important point, it seems to belong solely to Gilbert.

The directive property of the loadstone is one of the finest discoveries ever made by man; it gives to navigators an infallible method of recognising the direction of their track across the boundless ocean, in the darkness of night, and when fogs or tempests entirely obscure the heavens. A magnetic needle, balanced upon a pivot, points out the course to be pursued; and this valuable indication is as fully to be relied on, as even an observation of the stars. Previously to this useful and simple discovery, which was not made till the twelfth century, the sailor could not venture to a distance from the coast. The compass has enabled him to launch into the ocean itself, and to seek new regions, unknown to the most powerful nations of antiquity.

It is with this, as with most other useful inventions; we are ignorant of the person to whom society owes such an invaluable gift. We do not even know precisely what nation was the first to employ the polarity of the needle as a means of obtaining a fixed direction in space. The Jesuit missionaries assure us, that they formerly found among the Chinese traces of this method, which belong to a

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* Dr. William Gilbert, an English Physician, the friend of Bacon, who, about the year 1600, wrote a book upon magnetism that displays much talent.

very remote antiquity; but they supposed that it was employed merely as a guide on land; and that the Chinese had never thought of using it at sea, a thing much more important, without doubt, but which might have been less so to a people whose navigation seems to have been always very limited. But, be this as it may, we find evident proofs of the existence and nautical use of the compass, in Europe, towards the year 1150.

Such are the leading phenomena of magnetic attraction and repulsion; but, before reducing them to a general theory, we must attend to some other details, which could not have been sooner introduced without interrupting the general train of our reasoning.

146. It was long believed that iron and steel were the only substances that could be rendered magnetic; but it has lately been found, that nickel and cobalt possess the same property. Manganese, when reduced to a low temperature, is said to possess the same property. After these metals have been purified by very accurate chemical methods, needles may be formed of them capable of being magnetized and of directing themselves in the magnetic meridian very energetically, though with less force than needles made of steel; but from the nature of the process employed in the preparation of these metals, it is impossible to suppose that their action is due to the imperceptible portion of iron which may still remain in them. We shall soon see what is the origin of the magnetism attributed by several philosophers to copper, and some other bodies.

147. A magnetic bar of whatever metal loses its virtue when it is brought to a white heat. Not only is it incapable, when in this state, of attracting iron, but even if the iron itself is a magnet, it is not itself attracted; it remains insensible to the action thus exerted. This fact, which was known to Gilbert, may be confirmed in a very simple manner, namely, by placing the pivot of a small compass needle in a good spirit lamp, with one or more wicks, and surrounding the whole with a cylindrical glass to prevent any agitation from the external air. After having placed the needle horizontally upon a pivot, so that it can be shown to be sensible to the action of a loadstone, or a magnetic bar, placed near it, let the lamp be lighted. The needle enveloped in the flame, will soon become red hot; and if in this state the magnetic bar is again presented to it,

the needle will feel its influence, whether it is red, or bluish red; but when it reaches a white heat, it will become completely insensible to the presence of a magnet.

This result being obtained, remove the loadstone to a distance; and after having left the needle a short time exposed to the heat, extinguish the flame, and the needle will soon cool and become dark. But if, during this process, it is found to be pointing in a direction not exactly perpendicular to the magnetic meridian, it will have recovered some traces of magnetic power; and this power will be the more sensible, according as the needle is less or more remote from the magnetic meridian. Hence we may conclude, that this power has been restored to it by the influence of the earth itself. We see, therefore, that in the progressive cooling of the needle, there is a particular temperature at which it becomes sensible to the magnetic action, while it preserves sufficient ductility and softness to be affected even by a very feeble force; after which, the increasing hardness, produced by farther cooling, renders it fit to preserve, in all imaginable positions, the development of magnetism which is thus produced. This experiment, so remarkable for its consequences, is found in Dr. Gilbert's work.* Dr. Hook employed the same means for impressing magnetism upon bars of steel, by placing them in the direction of the magnetic meridian, at the moment when, after being suddenly heated, they were tempered in cold water; and Dr. Robison rendered the operation still more perfect, by substituting, in place of the weak action of the terrestrial globe, that of two powerful magnets, placed at the two ends of the red hot bars, at the instant they are plunged in water. Dr. Robison informs us, that they thus acquire a considerable degree of magnetism, a result quite conformable to the theoretical notions that may be deduced from the process of magnetizing bars, which will be soon explained. On this account, it may be important to try the method anew, as it may be found useful in magnetizing bars of a large size.

148. In this manner of operating, as well as in those which we have before described, the magnetism is developed either by the

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* Lib. iii. cap. 12.

influence of a magnet, or by that of the earth; but it appears that it may also be instantaneously excited by different mechanical means, as by the blow of a hammer, by pressure, by torsion, and by electrical discharges.

Having taken, for example, a common iron wire of two or three lines in diameter, and from 10 to 15 inches long, bend it by resting one of its ends upon a plate of iron, or rather put it through an opening in a thick iron plate, and bend and twist it in different directions till it is broken. It will be found to have acquired the magnetic virtue, as may be seen from its attracting iron filings, or from its attracting one end of a needle and repelling the other, when the twisted extremity is presented to it.

The same effect may be produced upon a rod of hard iron, by holding it in a vertical position, and striking its upper end slightly with a hammer. That the phenomenon may be very sensible, it is necessary that the rod be two or three feet long; and if it is afterward reversed, and the blows repeated upon its other end, it will gradually lose the magnetism impressed upon it, and will, by continuing the process, acquire a contrary magnetism, its poles being reversed. The same effect may be produced by letting it fall vertically upon a hard body. The utensils used by locksmiths almost always become magnetic, by the repeated blows to which they are subjected. Scissors, knives, and almost all cutting instruments, are more or less so particularly if they have been employed in cutting iron. In order to show their magnetic influence, they should be presented to a small magnetic needle, suspended horizontally by a single fibre of the spider's web, or by an untwisted fibre of silk, enclosed within a glass receiver to prevent any agitation from the air. The smallest magnetic force will thus attract one extremity of the needle, and repel the other. By this means it is proved, that every piece of iron which has suffered any friction becomes magnetic, and that an electrical discharge, acting like a blow, developes magnetism in iron wires through which it is made to pass. Lightning produces a similar effect upon the mariner's needle, and sometimes even reverses its poles. Perhaps, indeed, these different methods produce their effect by agitating the particles of the metal and thus disposing it to receive the influence of the terrestrial magnetism.

From these facts we might be led to conjecture, that the commu-

nication of magnetism consists in a particular kind of displacement effected among the particles of a bar of iron or steel. In order to determine this, M. Gay-Lussac endeavored to ascertain if these metals undergo any change of dimensions when they become magnetic. He took a hollow tube of iron shut up at the two ends, and to one of these ends he fitted a tube of glass extremely fine, and divided it into equal parts. He then introduced water into this apparatus till the tube of glass was partly filled; and having waited a certain time till the temperature of the liquid became uniform, he magnetized the iron tube. The surface of the water in the small tube did not experience any displacement, so that this change of state did not produce in the iron any appreciable change of bulk.

It is equally established, by means of the most exact balances, that the iron does not suffer any sensible alteration in its weight, in consequence of being magnetized; a result which might have been anticipated, from the striking analogy which subsists between magnetic attraction and repulsion and those which are produced by the equally imponderable principle of electricity.

The degree of proximity which exists among the particles of iron, nickel, and cobalt, has a great influence upon the facility with which they are rendered magnetic. These metals, when they are pure and perfectly ductile, do not retain their magnetism, but acquire and lose it instantaneously. They may be made, however, to preserve it, either by mechanical means, such as pressing, twisting, or rolling them; or, as has been observed by M. Gay-Lussac, by combining them chemically with substances not magnetic, as carbon, phosphorus, arsenic, and tin. As the proportion of these substances increases, the magnetism is communicated with more difficulty, and it also lasts longer; but at last there arrives a limit, when it is no longer possible to develope it in any sensible degree, and then the combination appears to be no longer capable of magnetic attraction. This property is only weakened, however, to a great degree without being entirely extinguished. For we can in this same state still obtain magnetic effects by means of more delicate tests that we soon shall make known.

From these phenomena, we should be led to infer, that whatever alters the state of aggregation of the particles of the metals, exerts

an influence upon their magnetic properties. The effect of temper is of a similar nature. To perceive the reason of this, we need only to be reminded of what it consists in.

149. When a bar of steel has been heated to redness, and allowed to cool slowly in the air, its particles, in approaching nearer and nearer to one another, take the distances and the positions of a stable equilibrium, to which they are gradually drawn by the slow and progressive effect of their reciprocal attractions. This is called the *annealed* state. But if we plunge the red hot bar into a fluid which cools its surface suddenly, the particles of this surface will take at first hurried arrangements, to which they are forced by this sudden change; and having thus become immovable, they form a kind of crust, to which the molecules of the interior of the mass are also constrained to adapt themselves with rapidity, in proportion as the cooling reaches them. Hence there results a kind of crystallization different from a stable equilibrium, as may be observed in Prince Rupert's drops, which are nothing else but tempered glass. Pure metals are incapable of acquiring temper, and the cooling, whether slow or sudden, does not alter their physical properties. Thus soft iron remains soft after being suddenly cooled; but iron, combined with carbon, and thus converted into steel, is changed by this operation, becoming more hard, more elastic, and more frangible, and to a greater degree, according to the suddenness with which it is cooled. Such a process may naturally be presumed to have an influence upon the magnetic properties, as it in fact has. The magnetic metals are magnetized with more difficulty when they are tempered, than when they are not; but the magnetism being once communicated, it is retained much longer. The difficulty of magnetizing increases with the hardness or temper; and this hardness has an influence also upon the intensity of the magnetism which the substances in question are capable of acquiring.

As the temper depends upon the difference of temperature to which the metal is subjected, it is important to find some way of estimating it. With respect to the liquid used in tempering, there is no difficulty; the inquiry relates to the metal, whose heat far exceeds the range of our thermometers. The common practice is to make use of the color acquired by the metal, as an indication of its temperature; and we say that it is tempered red-white, red, or

cherry-red, according to the tint acquired at the moment it is plunged into the liquid which is employed to cool it. Although this method is necessarily very imperfect, it is still sufficient, in most cases, for magnetic experiments, in which different degrees of temper have no sensible influence, except to a certain degree of temperature. The higher degrees do not change at all the intensity of the magnetism which bars are capable of acquiring, at least when they are magnetized by the processes hitherto discovered. This will be shown hereafter when the means of measuring this intensity are made known.

General Considerations respecting the Development of Magnetism. Resemblance to the Electric Pile.

150. The phenomena we have described have so striking a resemblance to those of the tourmaline and insulated electric pile, that similar theories, it would seem, ought to be applied to both. Of this we shall be more and more convinced by a stricter comparison.

In the first place, we recognise two distinct magnetic principles, of which each repels that of the same kind and attracts that of the opposite kind. These two principles exist originally in every bar of iron before it is magnetized, for there is no transfusion of magnetic principles in the communication of magnetism, and nothing either enters into the iron or goes out of it by contact. The two principles are therefore combined together, and each is disguised by the other like the natural electricities of bodies, for which reason they exert no action at a distance. This action, however, becomes sensible, when they are separated by any external influence which acts unequally upon the two, in the same manner as the natural electricities of bodies manifest their attractive and repulsive properties when they have been separated by the influence of an electrified body. These magnetic principles exist in this manner, and are thus developed separately in each particle of iron, without any transmission of magnetism from one particle to the other. For if a magnetic bar is broken into two or three, or any number of pieces, each of these pieces exhibits spontaneously two poles, like the frag-

ment of a tourmaline, or the elements of an electrical pile, and the poles of opposite names are formed at the ends of the particles which were previously in contact, in the same manner as happens in the tourmaline and in the pile. The act of separation, however, into several fragments, cannot have any influence in producing these poles; it only has the effect of displaying them, by withdrawing them from the attraction of the contiguous particles by which they were disguised in the entire magnetic column, in the same manner as the contiguous electrical poles are exhibited in the fragments of a tourmaline, or the elements of a pile. If we would establish this synthetically, we have only to join by their extremities several small bars of steel, and to magnetize them exactly as if they were one bar, either by placing the two extremities of the chain in contact with the opposite poles of two magnets, or moving over all its length one of the poles of a single magnet. Whatever be the method employed, the series of bars will be magnetized in the same manner as a continuous bar of the same dimensions, to which magnetism has been communicated in a similar manner. If we employ, for example, short pieces of tempered steel wire, about one twelfth of an inch in diameter, and which together make a length of about ten inches, we shall find in general that one end of the chain exerts the boreal magnetism, and the other end the austral magnetism; but if we break the chain, each piece of wire, disengaged from the influence of the other, will instantly exhibit two poles, and exert boreal magnetism in one half of its length, and austral magnetism in the other half.* If we now conceive the dimensions of these little wires diminished till they are reduced to a simple particle, we shall have an exact representation of the state of the particles of iron in magnetic bars, and we may then easily conceive how the system of all these little forces may, according to the proportions of those which follow one another, give opposite results at the two extremities of the bar, or even several results, alternately opposite in different points of its length.

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* A convenient way of performing this experiment, is to place the small pieces of steel wire in contact with one another, in a rectilineal groove cut in a piece of wood, and to fix them there with wax, in order that they may not separate when they are in the act of being magnetized.

151. When the two magnetisms have been separated, in the particles of a piece of hard iron or steel, experience proves that they unite with great slowness. It is necessary, therefore, that some cause, existing in the metal and peculiar to its substance, should oppose itself to that mutual action by which they have a tendency to unite. This cause, whatever it may be, is called the *coercive force*, and may be compared with strict analogy to the resistance which electricity meets with in moving along the surface, and in the interior, of resinous bodies. The stronger it is, the more difficult will it be to communicate the magnetic state, and the more durable and constant will this state be, as is the case with very hard steel. If, on the contrary, there were no resistance, the two magnetisms would separate in each particle by the smallest influence, and would re-unite as soon as that influence is withdrawn. This is the case with iron, cobalt, and nickel, when they have perfect softness. But even in this case no transmission of magnetism takes place between one particle and another. The composition and decomposition take place in the interior of each particle, and between the one and the other, there is an absolute impermeability. This is precisely what happens in the electric pile, formed by plates of glass, armed with metal. The decomposition and recomposition of the natural electricities are carried on with perfect facility between the metallic surfaces, which communicate with each other, without transmitting any thing through the insulating plates which separate them from the rest of the chain.

The observations which have now been made, appear to give a clear and precise view of the intimate constitution of natural and artificial magnets. It therefore remains for us only to determine by experiment the nature and the quantity of free magnetism in each part of the body, and the law which each species of magnetism follows in its attraction and repulsion. This second point, which can be directly ascertained in electrical experiments, cannot be here treated in the same manner; for, as we are not able to insulate one of the two magnetisms, we are are obliged to study the compound phenomena which result from their co-existence in those bodies where their distribution is known.

152. If we attend to the distribution of electricity in a state of equilibrium in conducting bodies, we shall see that it is subject to a

single condition, namely, that all the quantities of electricity which are free in the system, shall exercise no attractive or repulsive force upon any point in the interior of these bodies. In magnetism, it is not necessary to an equilibrium that there should be no interior action. It is only necessary that it be inferior to the resistance which the coercive force of the metal opposes to the separation or the re-union of the natural magnetisms. But this may take place in a great variety of ways, and even with interruptions in the development of the magnetism in the different points of the length of a bar; so that, in this general point of view, the question is absolutely indeterminate.

There is one particular case, however, which deserves to be considered, chiefly because it presents the limit of all possible cases, and is at the same time the most useful of them all, namely, where the quantity of free magnetism is such, that the sum of all the attractive and repulsive forces which result from it for each point of the bar, is precisely equal to the resistance which the coercive force opposes to the re-union of the natural magnetisms. When a bar is in this state, it is evident that it has in each of its points, the greatest quantity of free magnetism that it can admit; and hence it is said to be *magnetized to saturation.*

The most simple and infallible means of magnetizing to saturation, is to subject the bar of steel to so great a magnetic influence, that it shall produce instantaneously, in its particles, a more powerful decomposition of its natural magnetism, than that which can be maintained by the mere resistance of the coercive force. For, by withdrawing it from that influence, the first limit to the re-union of the decomposed magnetisms which presents itself, will be that which constitutes the state of being magnetized to saturation.

Of the Different Methods of Magnetizing.

153. Of all the methods of developing the magnetic forces, the most simple is that which we have explained in the first section. It consists in bringing the extremity *b* of a bar of steel or hard iron Fig. 98.
within a short distance, or even into contact with the north or south pole *A* of a magnet, *AB*. The free magnetisms in *A* and *B* act

upon the natural magnetisms of the bar of steel *a b*; but the pole *A* being nearest, its power will predominate, and the decomposition will be effected in every metallic particle of *a b*. The magnetism of an opposite name to *A* is attracted; that of the same name is repelled, and by a series of separations of this kind the extremity *b* of the bar acquires a pole of an opposite kind to *A*.

In order to be convinced of this, we have only to form with a steel wire a small needle $\alpha\ \beta$, about one-fourth of an inch long, and to magnetize it by rubbing it several times, and in the same direction, upon the pole *A*. When this needle, suspended by its centre with a single fibre of silk, is brought near the pole *A*, one of its extremities, β, for example, will be attracted, and will turn itself towards this pole; but if the same needle is brought near the extremity *b* of the bar, which has been in contact with *A*, it will immediately whirl round. The extremity β which was attracted by *A* will be repelled by *b*, and on the contrary, α will be attracted. If we continue to present this needle to different points of the bar *b a*, beginning at the extremity *b*, we shall find that through a certain length *b c*, the magnetism is of the same kind as at *b*, but an opposite magnetism will immediately succeed, for the needle will turn round and present its other pole to the bar. If the bar is short and the magnet powerful, this new state will continue without interruption to the extremity *a*, and consequently the bar will have in its second half *a c*, a magnetism of the same nature as *A*, and in its first half *b c* an opposite magnetism. The point *c* will be in a neutral state.

When the bar is very long, it often happens that the second state
Fig. 99. does not extend to the extremity, but only to a certain distance *c′*. Then the new magnetism which begins to show itself in *c*, exhibits, first, in departing from this point an increasing energy, manifested by the rapidity of the motions which it imparts to the small needle; but, afterwards, beyond a certain distance *a′*, this energy begins to diminish, and is nothing at the point *c′*, where the needle again becomes indifferent. Then succeeds another magnetism which is contrary to *A*, and to this succeeds sometimes even a fourth which is similar to *A*, and so on. The trial needle indicates these alternations by the inversions which it experiences at every change of magnetism; and the points of the bar *a b*, where this happens, are *consecutive points*.

If we suspend a bar of this kind for the purpose of determining its directive force, it is obvious that the parts situated on the same side of the centre of suspension, which have magnetisms of an opposite kind, will also have opposite tendencies, the one to bring the extremity of the bar towards the south pole of the earth, and the other towards the north pole. The total directive force of the bar will therefore, in general, be more weak than if each of its halves possessed throughout its whole length only one kind of magnetism. On this account, it is of the greatest importance to avoid consecutive points, not only in the formation of compass needles, but also in every case; for a bar will never produce the effect which might be obtained from it if these alternations did not exist. Whatever, indeed, be the kind of experiment for which we employ it, the poles of an opposite name will act always at the same time, and their action will be opposed to each other in proportion to their proximity, because their distances from the points attracted or repelled will then be less different. Hence, the most favorable arrangement of magnetism is, when only one kind of magnetism exists in each half of the bar; and, therefore, this mode of separation, produced to the greatest extent, is the object which should be kept in view in all our researches.

154. When we have magnetized a bar *a b* in the manner now supposed, by putting one of its extremities *b* in contact with one of the poles *A* of a loadstone, the consecutive points will be more easily formed, if the metal of the bar is hard either by its nature or in consequence of tempering. The reason of this is evident. The action of the loadstone *AB* decreases with the distance, and there is always a certain point of the bar *a b* where it becomes equal to the coercive force. Consequently, all the points situated beyond this limit would not undergo any decomposition of their natural magnetisms, if they were subjected solely to the influence of the loadstone *AB*; but the first part *b c* of the bar where the magnetism is already developed acts also upon these points, and tends to develope the opposite magnetism, and therefore, the resultant of this action commencing at a shorter distance than that of the loadstone *AB*, there must be a point at which it predominates, and it is there that the first alternation will take place, and this must occur the nearer to the point *b* according as the coercive force is greater; for,

if it were infinite, the magnet *AB* would only develope magnetism in the point *b* which is in contact with its pole *A*. The same reasoning is applicable to a comparison of the action exerted upon the rest of the bar by the first alternation *b c*, and the second *c a′ c′*. The predominance of this last over the following points, in consequence of its proximity, will be so much the more sensible as the coercive force is greater, and there will therefore be a greater facility in producing a third alternation *c′ b′ c″*. From this manner of viewing the phenomenon, the energy of the successive poles *a′*, *b′*, *a″*, *b″*, must diminish gradually in proportion as they are removed from the first extremity *b*, where the magnetism is most powerfully developed; as may be shown experimentally, by comparing the weights which adhere to the different parts of the bar, or by the oscillations of the trial needle.

The following experiment will, we trust, remove any difficulties that may appear to belong to this theory, as it proves that the same effects which we have described are produced by electricity.

Take a tube of polished glass several feet long, and having suspended it by silk threads, touch one of its extremities for some time with a stick of sealing wax, excited by friction. Upon examining the electrical state of the tube, we shall find that through a certain length from its touched extremity, it has the same kind of electricity with the wax. To this part there succeeds another, which possesses the opposite electricity, but in a weaker degree; and beyond this there will be found a third exhibiting the same electricity with the wax, but in a still more feeble manner. These alternations will continue to the other end of the tube, and will be proportioned in their number and extent to the force of the electricity which is employed. Here then we have the consecutive points of the magnet, with this difference only, that the electricity of the wax passes at first upon the glass, and extends over a certain length, because neither of these bodies resists entirely the direct transmission of electricity; whereas the particles of iron are rigorously impermeable to the transmission of magnetism. For this reason, the first alternation in magnetized bars acquires always a magnetism opposite to that of the pole of the loadstone which touches it, while the first alternation of electricity is of the same nature in the glass as in the wax.

155. All the phenomena of the composition and decomposition of the two electricities may, in general, be represented by the two magnetisms, with the modifications only which arise from absolute impermeability. As this analogy is of great importance in pointing out the truth of the theory, we shall now present some examples of it.

The first which we shall give is from Dr. Gilbert's work. Place a loadstone or magnetic bar *AB*, so that the two poles *A*, *B*, shall be in a vertical position, and taking two small pieces of soft iron wire *a b*, *a′ b′*, of the same length, and about an inch long, suspend both of them by untwisted silk fibres, *s a*, *s′ a′*, and bring them gradually near the pole *A*. When they are not very distant, as about the eighth of an inch, they will avoid one another as if they were mutually repelled, and the two suspended wires will diverge. The cause of this phenomenon is very simple. In proportion as the wire, *a b*, for example, approaches the pole *A*, its natural magnetisms will be decomposed by the predominating influence of this pole; *a b* will therefore become magnetic, and acquire two poles, one of which, *b*, is of an opposite name to *A*, and the other of the same name. The same thing will happen to the second wire *a′ b′*. The extremities of these two wires, which are in contact, will therefore suddenly acquire magnetisms of the same name, and therefore will repel each other; and this cause, favored by their small size, and the mobility of their suspending fibres, will show itself by their divergence. Fig. 100.

Here, then, is an exact representation of the electric influences, with this difference only, that there is no real transmission of magnetism into the different parts of the wire *a b*, but simply a decomposition in each particle; a decomposition, in virtue of which one of the two kinds of magnetism becomes free in *b*, and the other in *a*, while the opposite magnetism is disguised.

Let us now take two plates of steel *AB*, *A′ B′*, of the same length, and very thin, like that which is used for watch springs. When both of them are magnetized in the same manner, by putting them in contact with the same pole of the same loadstone, or by rubbing them in the same direction on its surface, let it be ascertained what weight either of them, for example, *AB*, is capable of supporting by its pole *A*, and then suspend from this pole a soft Fig. 101.

iron wire $b\ a$, whose weight is about 50 or 100 times less. When this is done, bring the second plate $A\ B'$ slowly towards the first, or if you please, place the one upon the other, with their opposite poles coincident, and when they come in contact, the adherence of the wire $b\ a$ will be almost entirely destroyed; so that the system of two magnets thus combined can only support a very small portion of the weight, which each of them would have supported separately. This phenomenon is easily understood. For if these two plates, being equal in dimensions and magnetic energy, are so placed, that their opposite poles act simultaneously on ferruginous particles which are exactly, or very nearly, equidistant, it is clear that their actions would neutralize each other, as if the united plates formed a uniform mass in which the boreal and austral magnetisms were combined. This phenomenon is entirely analogous to that heretofore
41. described, respecting the contact of two glass plates charged with opposite electricities by mutual friction, and it is evident, that the same explanation applies to both.

We have supposed the two plates to be very thin, in order that their distance, at different points, from the wire $a\ b$, may be nearly equal, when they are placed upon one another. Indeed, in the second plate $A'\ B'$ this distance is unavoidably greater by the whole thickness of the first AB; and it is from this cause that the actions of the two equal plates are not exactly destroyed. This inequality of action, however, though it cannot be removed, may be diminished by diminishing the thickness of the plates; or the same effect may be produced by taking a second plate $A'\ B'$ more powerful than AB. The wire $a\ b$ will then fall of its own accord, when the action of the plate $A'\ B'$, diminished by the excess of distance, becomes equal to the action of AB, which will happen either at the instant of the contact of the two plates, or before it. In this case, if the distance of the two plates is farther diminished, the action of the second will finally preponderate, and the wire $a\ b$ will return again to attach itself to the pole A, but with a magnetism opposite to that which it had at first. It is easy to vary these phenomena; but the two experiments which we have described will suggest the explanation to be given in all other cases.

156. We have already remarked, that a loadstone loses nothing by being employed to magnetize any number of bars; on the con-

trary it will be seen, that the effect of these repeated operations, instead of diminishing, rather increases its energy. When the pole of a loadstone touches the extremity *b* of a bar, and developes in it a magnetism contrary to that which it possesses, this magnetism, in its turn, acts upon the natural magnetism of the loadstone which produces it, and tends to excite in it a new decomposition, which augments the free magnetism of *A*. This augmentation produces in the bar *a b* a new decomposition, which again re-acts upon the pole *A*, so that both of them, by this mutual re-action, acquire a more intense degree of magnetism than they would have done by the direct action of *A*. This is perfectly analogous to the increase of charge which the upper plate of an electrical condenser receives from the action of the electricity which is disguised in the lower plate; but the electric equilibrium establishes itself instantaneously in the plates, because they are composed of materials capable of transmitting electricity with extreme facility; whereas the maximum charge of a loadstone, and of the bars which touch it, is produced slowly. For, on the one hand, if these bars are made of steel or hard iron, the coercive force opposes itself to a ready decomposition of their natural magnetisms; and on the other hand, the substance of the loadstone opposes to the increase of its magnetism a similar resistance. The first of these obstacles may be destroyed by making the bars of very soft iron, but the second is unavoidable; and it follows from this, that it must require a good deal of time, for the system to develope all the magnetism which it is capable of acquiring. Fig. 98.

This remark will serve to explain several important phenomena. Suppose a small piece of soft iron to be applied to one of the poles of a natural or artificial magnet, and from this iron a small balance scale to be suspended, in which are placed successively different weights. If at first we put into this scale the greatest weight it is capable of supporting, it will be found that this weight may be increased by a very small quantity every day; but if, at the end of some weeks, or even months, we forcibly detach all the iron, and try again to replace it, we shall find that the magnet is no longer capable of supporting it. It will lose instantly all the excess of force which it had acquired by the influence of the iron. Indeed, under this influence the two magnetisms, partly disguised by those

of the iron, can exist in a state of decomposition which the coercive force alone is no longer able to maintain; the magnet, therefore, abandoned to itself, must return to the maximum of magnetic force which the nature of its substance admits, that is, to its state of saturation, and what is very important to remark, the restitution appears to take place instantaneously.

This principle has been very advantageously employed to increase the force of natural and artificial magnets, by fitting them up with what is called *armatures*. An armature consists of pieces of very soft iron, applied to the polar faces of the magnet, which, becoming themselves magnetic by influence, increase its energy every day. Let us take a loadstone of a square form, such as $AA'''\ BB'''$,
Fig. 102. having AA''' for its north, and BB''' for its south pole. Let us now suppose at first, that we apply to the first of these poles an armature of soft iron $A'\ A''\ A'''$, of the form indicated by the figure, the natural magnetisms of this plate will soon be decomposed; its boreal magnetism will be attracted by the austral magnetism which prevails in AA''', and its austral magnetism will be repelled, so that this last will predominate over all the exterior surface $A'\ A''\ A'''$ of the plate of iron, but principally in the most distant extremity $A'\ A''$, which is called *the foot of the armature.* Let us now envelope with a similar armature the other pole of the magnet BB'''; a similar decomposition will be produced, and the foot $B'\ B''$ will acquire boreal magnetism. After some time, the influence of the armature will have produced a perceptible decomposition of magnetism in the particles of the magnet which it envelopes, and this will be considerably stronger. This envelope should not be too thin; for, all circumstances remaining the same, the development of magnetism capable of being produced in a piece of iron depends upon its mass; moreover it should not be too thick, as the greatest energy of the action does not reside upon the lateral surface, but in the feet $A'\ A''$, $B'\ B''$. The advantages of this circumstance we shall soon have occasion to explain. Generally, the proper thickness of the armature of each magnet is to be determined by experiment. It is very evident that this armature ought to be made of soft iron, in order to facilitate the decomposition of magnetism. Steel and hard iron would be altogether hurtful, though they have been recommended by some writers.

157. The arming of magnets not only increases their force by a new disengagement of the magnetism which it excites, but it increases it also by giving a better direction to the magnetic forces. Let us suppose, for example, that we wish to make use of the unarmed magnet *A′ ABB* in magnetizing the bar *a b*, by presenting the northern face *BB* to one of its extremities. It is manifest, from an inspection of the figure, that the greater number of points of this face, as well as the points beyond them, will act very obliquely upon the bar, and will consequently have little influence in decomposing, by their attraction, the magnetism of its particles in the direction of its length *a b*. Besides, the austral surface *AA*, which is parallel to the first, will oppose this effect by its contrary influence; and though its action is more feeble, because it is exerted at a greater distance, yet it has the advantage of a more favorable direction, from its acting at smaller angles with the length of the bar. On the contrary, when the opposite energy of the two poles is turned aside, and carried in a great measure into the feet of the armature, let the bar *a b* be held in the prolongation of one of the feet *B′ B″*, as represented in figure 102; we shall first perceive, that the action of this pole, concentrated as it is in the foot, will act much more nearly in the direction of the length of the bar, than the large surface of the magnet *BB* did; and, on the contrary, the action of the other pole *AA′*, carried into the corresponding foot *A′ A″*, will act much more obliquely on the bar than it did in the case of parallelism; the latter will, therefore, have much less influence in opposing the immediate action of the foot to which the bar is applied. By these means, we are able to communicate to a bar a much higher degree of magnetism than could have been done with the same magnet unarmed. We shall be convinced of this if we compare by the method of horizontal oscillations the intensities of the directive forces which the same bars acquire, when magnetized successively in these two ways. In order to preserve a magnet of this kind, we must apply to its two poles a parallelopiped of soft iron, which answers the purpose of an armature, and which is taken away when we mean to employ the power of one of its poles. The preserving influence of this parallelopiped is founded upon the same principle as the use of the armature. Fig. 103.

In this manner we obtain the highest degree of magnetism which

can be produced by simple contact; but the necessity of communicating to compass needles the highest possible energy has given rise to various other methods, which we shall proceed to describe.

158. The first method of making artificial magnets, which was for a long time almost the only one, consists in applying the plate or bar of steel at right angles to one of the poles of either a natural or artificial magnet, and rubbing it upon this pole in the direction of the length of the bar, as represented in figure 105. In order to estimate the effect of this method, let us consider the bar *a b*, when its extremity *b* is first applied to the pole *A*, of the magnet *AB*, and let us suppose that *A* is the south pole of this magnet. In this case, the austral action of the part *CA*, predominating over the boreal action of the portion *CB*, will produce in *b* a decomposition of the natural magnetisms of the plate; the austral magnetism of each particle will be repelled towards *a*; the boreal magnetism will be attracted towards *b*, and it will form in *b* a north pole. But when the pole *A* quits the extremity *b*, and begins to move over the succeeding points of *a b*, it will produce upon each of them the very same effect; that is, it will attract the boreal magnetism of each particle to the actual point of contact, and will repel from it the austral magnetism. But the continuance of this repulsion will at last be found to have destroyed entirely the first decomposition of magnetism which had been produced by immediate contact with the extremity *b*. According as it advances on the plate, the pole will continue to produce the same effect, and to destroy successively, by its influence at a distance, the decomposition which had been produced by contact with the points previously touched. But this cause of destruction will not take place for the extremity *a* of the bar which arrives last at the pole *A*, in the position *b′ a′*. The effect of immediate contact will follow in its stead; and upon quitting the magnet, it will preserve the development of boreal magnetism which had previously taken place. Hence it is almost entirely to this last effect that the action of the present method is limited; and consequently, we should not expect more success than from the method of simple contact which we first employed. This result may be confirmed by experiment; for if we measure by means of the torsion balance the directive forces obtained by this method, and compare them with those derived from the other methods which we

are about to describe, we shall find that it is not capable of magnetizing to saturation any needles but such as are very thin.

This method has also the disadvantage of producing consecutive points frequently and easily, like the method of simple contact, particularly if the plate of steel is long and hard, and the magnet is kept longer on one point than on another. This last circumstance is sufficient of itself to produce these points; for if we take a plate of steel that has been regularly magnetized, that is, which has in each of its halves the same kind of magnetism, and apply one of the poles of a needle to any part of its length, a pole will be created in these points of an opposite name to that of the pole applied; at least, if the magnet is more powerful than the plate. If the magnet is very powerful, and the plate not thick, it is sufficient to apply it to the middle of its length, in order to create in this point a pole, and two opposite poles at the two extremities, as may be verified by the trial needle α β, which we have already employed.

159. The method of making artificial magnets which we have described presents a remarkable phenomenon. When the plate *a b*, has been thus rubbed upon one of the poles of a very strong magnet, on the north pole, for example, and has consequently received a high degree of magnetism, let it be rubbed along its whole length, and in the same direction, upon the homologous pole of a weak magnet. We should be led to believe that this operation, performed in the same direction as the first, would augment its magnetic state, or at any rate, would leave it as it was before; but it actually diminishes it, and the magnetism is reduced to the same intensity as if the plate had been magnetized by the weak magnet. In order to understand this phenomenon, we must consider, that the second magnet in touching successively every point of the first half of the plate, creates for a moment by its contact, a magnetism opposite to that which the first magnet had left in it; at least, if we suppose that the second magnet is formed of steel sufficiently hard to prevent its own magnetism from being destroyed by that of the plate. This local inversion is produced constantly, though the second magnet is weaker than the first, because it acts successively on each point by immediate contact, whereas the first magnet produced the final state of magnetism by acting at a distance. While, therefore, the second magnet rubs upon the first half of the plate,

by touching it with its north pole, each point which it touches is, at first, brought back to its natural state, and then passes to the austral state, and receives afterwards, by influence at a distance the final degree of boreal magnetism which the magnet is capable of giving it, by combining its action with that magnetism of which it had already been rendered free. But, as these successive changes of free magnetism cannot take place in the one half, without creating corresponding changes in the other, it is obvious that the plate, after having experienced this disturbing force over the whole of its length, will be brought back precisely to the same degree of magnetism as if it had been touched only by the second magnet. It is manifest, also, that this reduction will not take place if the north pole of the second magnet touches the plate only on its south half; for then the magnetism of the latter will be rather augmented than diminished. For the same reason, there will be no longer any diminution, if the magnetism of the plate were sufficiently strong to destroy that of the second magnet and reverse its poles. The extreme case of this supposition will happen when this magnet is made of very soft iron, in which the decomposition and recomposition of the natural magnetism may take place with extreme facility; for then, as this iron passes over the different points of the plate, it will acquire, at the moment of contact, a magnetism opposite to that of the point which touches it, and consequently, by its reaction, it will tend to augment the species of magnetism which this point already possessed. This would be, as it were, a movable armature, applied in turn to different points of the plate; and we think there can be no doubt that this repeated friction, instead of diminishing the magnetism of the plate, would soon bring it to its maximum.

160. After many fruitless attempts to modify and bring to perfection the method of making artificial magnets by simple contact, the first step towards more complicated and better methods, was made in 1745 by Dr. Gowan Knight, of London. Having joined by their ends two bars strongly magnetized, the north pole of the one touching the south pole of the other, he placed upon these bars, and in the direction of their length, a small bar of steel, tempered at a cherry-red heat, the middle of which corresponded to the point of junction of the two large bars; and, separating the bars, he rubbed each of them upon the corresponding extremity of the small

bar, which was found to acquire by this operation a more intense degree of magnetism than had hitherto been obtained.

In this process, each magnet acts upon the half of the small bar which it passes over, as in the first method; but, in that case, the influence of the same magnet acted alone over all the length of the plate, in order to develope the two magnetisms; whereas, in the new method, this decomposition is favored by the presence of the other magnet; for in all the points which lie between them, their influence is combined, and the kind of magnetism which is attracted by the one towards one extremity of the bar, is at the same time repelled by the other towards the same extremity. By employing this method, and making use of large bars strongly magnetized, it is found that small bars when they are short, and not very thick, acquire nearly a maximum of magnetism; but it is impossible by this process to magnetize a long bar to saturation.

The discovery of Dr. Knight led, at this period, several philosophers to seek other means of obtaining the same degree of magnetism in larger bars. M. Du Hamel, of the Academy of Sciences of Paris, having united himself with Antheaume in this inquiry, contrived the following method. Having placed parallel to each other two bars of steel of the same length, AB, $A' B'$, he united their Fig. 106.
extremities by small parallelopipeds F, F', of very soft iron, so as to form a right-angled parallelogram. He then took two bundles of bars $a\ b$, $a'\ b'$, previously magnetized, and united their poles of different names towards the middle of one of the bars of steel; after which, inclining the bundles as represented in the figure, he carried them towards each extremity of the bar; and by a successive repetition of this friction upon each bar of steel AB, $A' B'$, he obtained a considerable degree of magnetism. In this arrangement, each bundle acts upon the half of the bar, which it passes over as in the first method. The employment of two bundles instead of one has also the same advantage as the method of Dr. Knight; but the application of two small bars of iron to the extremities of the bars of steel is a very important addition; for as soon as the bars of steel have acquired any degree of magnetism, these small bars of soft iron, magnetized also by influence, will themselves act upon the steel bars like a real armature; they will fix in each of their extremities the magnetism already developed; and, neutralizing it, they will

give to the moving bundles a greater degree of facility in effecting a new decomposition of the magnetism by a new friction. There was now only one step to be taken, in order to give to this method all the perfection of which it is susceptible. It was only necessary to substitute in the place of the small bars of soft iron two strong magnets, with their poles opposite to each other, in order to retain and neutralize still more strongly the magnetism previously decomposed by rubbing bundles. This improvement, as we shall presently see, was made by Æpinus. But when large magnets cannot be obtained, the method of Du Hamel is the best which can be employed for magnetizing compass needles, and plates which are not more than one-eighth of an inch thick, provided that the moving bundles are strongly magnetized.

161. About the same time that M. Du Hamel was occupied with these researches at Paris, Mr. Michel and Mr. Canton were pursuing the same object in England.

Mr. Michel employed two bundles of bars, strongly magnetized, and placed parallel to each other, the poles of different names being united at each extremity ; in such a manner, however, that there remained an interval between them of about one-third of an inch. He then placed, in the same straight line, several equal bars which he wished to magnetize, and caused to pass over these bars at right angles, and in the direction of the line formed by them, one of the extremities of the double bundle. By this method, he found that the intermediate bars in the chain acquired a great magnetic force. The magnetism, however, which is thus obtained, never rises to the maximum of saturation.

The different bars placed in contact by their extremities, have here the same effect as the small bars of iron employed by Du Hamel. They perform the part of a real armature ; but as the nature of their substance does not permit the free development of magnetism, they do not become magnetic, and they do not act till they have been touched by the moving bundles. Hence we perceive why the intermediate bars in the series are the only ones that are strongly magnetized, for they are the only ones which are armed. In this respect the method of Michel returns to that of Du Hamel, and is perhaps inferior to it ; but it presents another modification which deserves to be examined, viz. the employment of two parallel

bundles kept at a constant distance by their opposite poles, and rubbing simultaneous'y over the whole extent of the bars. In order to conceive distinctly the effect of this arrangement, let us represent the two bundles by AB, $B'A'$; let us suppose that the poles pass over the bar of steel $B''A''$, and let us analyse their action upon the points of this bar, both within and without the interval which they comprehend. Fig. 107. 108.

We shall first consider the bundle AB, which we shall suppose not to have any consecutive points, so that the half CB, which is the most distant from the bar shall possess the boreal magnetism, and the nearest half CA the austral magnetism. If m is any particle of the bar $A''B''$, all the points of the bundle AB, whether this particle be within the bundles, as in figure 107, or without them, as in figure 108, will exert upon the natural magnetisms of this particle a boreal or austral action, and will tend to separate them according to the nature of the action. But if the two halves of this bundle possess nearly equal degrees of magnetism, as they must do, since we suppose that the point of indifference falls nearly in the middle of its length, it is evident that the austral action must predominate over the other, because the points which exert it are nearer to the particle m, so that the final and total action of the bundle AB, will have for its resultant an austral force, directed according to a certain line $o\,m$, which will cut AB in the austral portion, at a little distance from its extremity; for, in magnets that have no consecutive points, the quantity of free magnetism is the greatest possible at the extremities themselves, and thence decreases towards the centre with extreme rapidity, like the free electricity in the tourmaline, and in insulated electrical piles. 93.

Now, if we consider the action of the other bundle $A'B'$ upon the same particle, we shall see, in like manner, that there will result from it a single boreal force, whose direction, represented by $m\,o'$, will cut this bundle in its northern half at a little distance from its extremity.

In order to find the joint effect of these two forces in the direction of the bar's length $A''B''$, we must decompose them in that direction. If we represent them by $m\,r$, $m\,r'$, each of them will give a force $m\,f$, $m\,f'$, perpendicular to the direction of the bar, and a boreal or an austral force $m\,s$, $m\,n$, in the direction of its length.

These last forces are the only ones with which we are concerned, as they alone determine the longitudinal decomposition of the magnetism. If we compare the figures we shall find that if the particle *m* is situated within the bundles, as in figure 107, the two forces *m n*, *m s*, unite to decompose its natural magnetisms in the same direction *a b*; the boreal magnetism being attracted in the direction of the extremity *b* of the particle, situated towards the part *B''* of the bar, and the austral magnetism in the direction of the extremity *a*, situated towards the part *A''* of the bar. It is likewise evident, that this effect will take place upon all the other parts of the bar to which the two bundles may be carried. If the particle *m*, on the contrary, is situated without the interval comprehended between the two bundles, as in figure 108, the longitudinal actions of the bundles will oppose each other, and the action of the nearest one, for example, will predominate in consequence of its proximity, and there will result a momentary decomposition of magnetism opposite to that above supposed; for the austral magnetism will be carried in the direction of the extremity *b* of the particle, situated towards the part *B''* of the bar, and the boreal in the direction of the extremity *a* situated towards the part *A''*. This decomposition, however, produced by the difference of the forces, will always be weaker than the first, which is produced by their sum; and this will be particularly the case, if the rubbing bundles are placed at a small distance from each other; for their opposite influence will then become almost equal upon the points of the bar which are ever so little distant
Fig. 108. from their poles *A*, *B'*. The feeble development of magnetism which thus takes place in *m*, cannot resist the combined action of
Fig. 107. the two bundles when they are carried to *m*, and that point is comprehended between them; and reciprocally, when they leave the
Fig. 107. point *m*, they cannot destroy in it all the development of magnetism which they had before produced by exerting upon it their united influence. When this operation is frequently repeated from one end of the bar to the other, it will always tend to excite an increasing development of magnetism; and experience proves that this development becomes very considerable. In order that it may be equal in the two halves of the bar, the united bundles must be first applied at its centre, and an equal number of similar applications must be made upon each half of the bar. The bundles being then

brought back to the centre, they must be lifted up vertically, so as not to disturb the longitudinal effect which had been previously produced. This method, called by its inventor the *method of double touch*, has obtained a great degree of celebrity.

162. Mr. Canton published a modification of this method; but it had only the appearance of novelty. He formed at first, as Du Hamel did, a right-angled parallelogram, by uniting the extremities of the two steel bars with pieces of soft iron; he then touched these bars with two parallel bundles, united according to the method of Michel, and then separating the bundles, and inclining them on both sides to the bar, he moved them each way towards the extremities. But from what we have already said of the effect of repeated frictions with magnets of unequal strength, it is obvious that the last operation, with the inclined bundles, is the only one which determines the final magnetic state of the bar. The preceding modification, therefore, of the method of double touch is quite useless, and the operation, deprived of this superfluous addition, is identically the same with that of Du Hamel.

163. Æpinus made a modification of the method of double touch much more happy, and better contrived. He caused the poles of the two bundles to move at a small distance from each other without ever separating them; but he inclined the bundles in opposite directions, as Du Hamel had done, and as is represented in figure 109. By this means, the resultant of their action upon each particle *m* became more oblique to the surface of the bar, and consequently the part of this resultant which is exerted in a longitudinal direction became more considerable. It is true, indeed, that the proper action of each point of the bundle was at the same time diminished, because, it being necessary, in order to incline it, to turn it upon one of its edges, this motion necessarily separates each of its points from the particle *m* upon which it was to act. But notwithstanding this circumstance, we find that to a certain limit of inclination, the oblique position is on the whole advantageous. Experiment alone is capable of indicating the most favorable limit. Æpinus decided upon an inclination of 15 or 20 degrees to the surface of the bar; and this seems to be the most advantageous, though from the nature of a maximum, any small variation in the angle will not perceptibly alter the result. Æpinus added to this modification

the employment of armatures, but he advantageously substituted, in place of the soft iron of Du Hamel, two strong magnets, with their opposite poles united, as we have already stated. The combination of these two operations constitutes the method to which his name has been given. In examining the results which it produces, it has been found superior to every other method, when we wish to magnetize very large bars with bundles of plates that have a feeble magnetism ; but it is necessarily attended with some inconveniences, which it is of importance to notice. The first of these is, that it never produces a development of magnetism perfectly equal in the two halves of the bars to which it is applied. If we place these magnetized bars indeed horizontally, under a sheet of paper covered with very fine iron filings, we shall see from the manner in which they are grouped, that the neutral point is not exactly in the middle of the bar, but is, as Coulomb observed, somewhat removed toward the extremity last magnetized.

It appears, in the second place, that the method of Æpinus produces consecutive points, in very long plates, more readily than that of Du Hamel. These alternations have, indeed, in all cases very little energy ; but they nevertheless diminish the directive force, which is a matter of great inconvenience in the construction of compass needles. The same thing may be said of the other small inequality in the distribution of the magnetism ; and, therefore, it is much better to magnetize needles by the method of Du Hamel, which is completely exempt from these two faults, and reserve the method of Æpinus for large bars, to which we wish to communicate a very great force, for then it is of little consequence whether or not the neutral point is placed exactly in the middle of the bar.

164. By thus taking from each of these methods what is most useful, and adding to them the information obtained from long experience, Coulomb arrived at the following arrangements.

In order to form fixed bundles, he employed for each ten bars of steel tempered cherry-red, having a length of about 21 or 22 inches, a breadth of about six-tenths of an inch, and a thickness of one-fifth of an inch. He magnetized them as highly as he could with a natural or artificial magnet, and then, uniting them by their poles of the same name, he formed two beds of five bars each, separated by small rectangular parallelopipeds of very soft iron, which performed

the part of a common armature, and which projected a little beyond their extremities. See figure 110.

Biot found that he might advantageously substitute for these parallelopipeds, plates of soft iron, which unite at the extremity of the magnet, into one mass, forming a truncated pyramid. This disposition of the bundles, by which the magnetic forces are concentrated, is represented in figure 111.

The moving bundles he commonly formed of four bars tempered cherry-red, about 16 inches long, and one-fifth of an inch thick, and six-tenths of an inch wide. After magnetizing them as strongly as possible, he united two of them by their widths, and two of them by their thicknesses, which gave to each bundle a width of one inch and two-tenths, and a thickness of two-fifths. It is evidently advantageous to apply to them a common armature of soft iron of the same form as that of the fixed bundles.

Both the fixed and movable bundles were made of a steel, well known in commerce from a stamp of seven stars. It is of a moderate quality, but Coulomb observed, as had already been done before, that every kind of steel, provided it is not of a very bad quality, takes nearly the same degree of magnetism. We shall only remark, that as bars are always bent a little in tempering, they should be tempered at first as hard as possible, and then annealed to the first shade of yellow. This annealing gives them malleability sufficient for forming them again into shape, and at the same time leaves a coercive force sufficient for preserving a very energetic development of magnetism.

In order to magnetize a needle or a bar of any kind by means of this method, we begin by placing the large bundles in the same straight line, so that their north and south poles are turned toward each other, and kept at a distance equal to the length of this bar, as in figure 112. Each of its ends is then placed upon one extremity of the armature, in such manner as to lap a little over it; after that, two movable bundles are placed upon the centre of the bar, and inclined each way in opposite directions, so as to form with it an angle of about 20° or 30°. Then, if we wish to employ the method of M. Du Hamel, we must cause each bundle to move over the half of the bar on which it is placed; but if we wish to employ that of Æpinus, we do not separate them, but place them,

together with a small piece of wood or copper between them, in order to keep their opposite poles at a distance of about one-fifth of an inch; and holding them in this manner, with the same inclination as in the other method, they are moved successively from the centre to each extremity, so that the number of applications upon the two halves of the bar may be equal. After the last motion by which they are brought to the centre, they are withdrawn perpendicularly, and the same operation is repeated upon each of the other surfaces.

165. If the bars which compose the bundles have not been at first magnetized to saturation, which will generally happen when we have not at our command an apparatus like the preceding, their assemblage will produce, in bars subjected to their action, a much stronger degree of magnetism than they themselves possess. These new bars may then be used in forming other bundles, stronger than the first; and if we have not yet attained the maximum of energy, we may repeat the operation a second, a third, or even a fourth time, till we have obtained bundles as strong as we can desire.

We have said that each moving bundle was composed of four bars. When we wish, however, to magnetize very thick bars, we must unite a greater number, arranging them in steps retreating about half an inch in the direction of the thickness, as is shown in figure 113. This arrangement is founded on the fact, that the greatest development of magnetism takes place at the extremities of the bars. In this case, the bar nearest to the central one tends to maintain, and even to augment, at its extremity, the development of magnetism which already resides in it. The third bar produces the same effect upon the second, and so on with the rest. In order to concentrate still more the action of these bars, we may unite them by pyramidal armatures of soft iron, resembling those we have before described.

When we have finished the operation, either with the system of fixed or movable bars, we must place the two of each pair parallel to each other, similar poles being in opposite directions, as represented in figure 114. The poles are then joined by parallelopipeds of soft iron, which, becoming magnetic by influence, neutralize the magnetism of the bundle, and tend to increase rather than to diminish it. The effect is precisely the same as that which we have ex-

plained above, in speaking of the increase of force which natural loadstones acquire by time, when the feet of their armature are united by pieces of soft iron.

Coulomb has verified all these theoretical considerations by the most delicate experiments, in the course of which he has applied the several methods of making artificial magnets to bars of the same nature and the same dimensions; and the intensity of the magnetic charge was readily measured by means of horizontal oscillations, as heretofore explained.

These methods show that the experiments of Du Hamel and Æpinus, are superior to all others; inasmuch as they impart an equal degree of magnetic power with a much smaller number of movable bars. It will be seen that the two methods are equally good, so long as we wish to operate on bars of only about an inch in thickness; but in applying them to bars of greater thickness, the method of Æpinus is decidedly the best. It would be of little use to increase the thickness of the bars in the magnetic apparatus to beyond three or four inches; for experiments show that we shall obtain a much greater intensity of magnetic force by uniting many small bars magnetized separately before being united; and this evidently results from the fact, that we can communicate a much more powerful magnetic force to a single bar, than to a bar placed between a number of others.

166. In the foregoing remarks I have supposed the process of magnetizing to take place at the ordinary temperature of the atmosphere. But perhaps a still greater development of magnetism might be obtained by raising the temperature of the bars while the process is going on, or by altering the nature of the substances used as bars. The first suggestion was made by Robison; the second has been practically applied by Knight; and it would seem, that his success has been such, that the experiment deserves to be submitted anew to the most rigorous examination. The process of Knight differs from the ordinary one, in requiring as a substitute for steel, a paste made of the deutoxide of iron pulverized, and mixed with linseed oil. This paste dried by a gentle heat, acquires after a few weeks, according to him, an intensity of magnetic force of which it is exceedingly difficult to deprive it.

General Distribution of Free Magnetism in Wires Magnetized by the method of Double-touch —Laws of Magnetic Attraction and Repulsion.

167. If, after having magnetized, by the method of Du Hamel or that of Æpinus, a steel wire 15 or 20 inches long, and one or two lines in diameter, we examine what weight it is capable of supporting at different points of its length, we shall find that this weight goes on increasing from the extremity of the wire for the space of four or five lines, beyond which it diminishes rapid'y, so as to become almost insensible at the distance of two or three inches from the extremity. These weights will also be found to be equal towards the ends of the wire; and hence it follows, as we had foreseen, that the most intense quantities of free magnetism are distributed towards the two extremities, and at a small distance from them, and that they are sensibly equal there,—a distribution perfectly analogous to that of free electricity in the tourmaline and electric piles.

This important result may be proved in the most satisfactory manner by the torsion balance. The experiment, as performed by Coulomb, is represented in figure 115. Having adapted to the stirrup of the magnetic balance a suspension wire, whose force of torsion is very small, we place in it a steel wire $a\ b$, strongly magnetized by the method of Du Hamel or that of Æpinus. In the direction of the magnetic meridian of this wire, which ought to correspond to the zero of torsion, a vertical rule RR of wood or copper, one or two lines thick, is so fixed that the extremity a of the horizontal wire may come close to it, when it is brought back to the magnetic meridian. On the other side of this rule, and along a groove made in it for the purpose, a magnetized steel wire $a'\ b'$, such as we have above described, is made to pass vertically, so as just to present its homologous pole a' to that of the needle. The needle will at first be repelled by the similar magnetism of a', but it is forcibly brought back to the rule, by twisting the suspending wire in such a manner that there shall remain only the thickness of the rule, or a distance of about two lines between the nearest points of the wires.

But since the wire *a′ b′*, which we have placed behind the rule, is vertical, while the wire *a b* is horizontal, the several points on each side, which are distant four or five lines from the intersection, contribute very little to the repulsion, on account of the distance, and the obliquity with which they act; so that the force of torsion which is required in order to maintain the contact, must depend principally on the quantities of free magnetism which exist in the two needles, from the point of intersection to a distance of two or three lines on each side of this point. By thus making the wire *a′ b′* pass vertically along the rule, presenting successively its several points at the small distance of two lines from the same point of the wire *a b*, whose action remains constant, the force of torsion which it is necessary to employ in order to preserve the position of *a b* against the rule, will be, in each case, a very exact measure of the intensity of free magnetism in the point of the wire *a′ b′* which corresponds to the intersection. In making this experiment it will be found, that if eight circles of torsion are necessary when the intersection is two lines from the extremity of the wire *a′ b′*, two or three circles only will be necessary at two inches; and when the extremity of the wire *a′ b′* is three inches above or below the horizontal plane of *a b*, the repulsion is almost nothing. It follows, therefore, from this trial, that the free magnetism of *a′ b′* is chiefly concentrated upon the first three inches from the extremity. A similar result will be obtained from the attraction of the opposite poles; and if the vertical wire has been regularly magnetized by the process of double touch, it will be found that the attraction of the pole *b′* is sensibly equal to the repulsion of the pole *a′*; but it is necessary to observe, that in order to obtain correct results, we must employ only needles or wires of excellent steel strongly tempered; and we must take care not to give them a high degree of magnetism; for without these precautions, the points of intersection being only two lines distant, the reciprocal influence of the needle and the steel wire may develope in these points new quantities of magnetism, so that the intensities of their attraction and repulsion would not remain constant during the experiment.

If, in the preceding experiment, we employ two similar wires, 24 inches long, and placed so that the points of intersection shall be 10 or 12 lines from the extremity; then, by bringing together their

homologous poles, there will be a repulsion. But this repulsion will arise almost entirely from the two or three inches of length upon which the magnetism is most developed ; and the effect will be produced almost entirely by the contiguous poles ; for the action of the two others will be extremely weak, both on account of the length of the two wires, and on account of the obliquity of their direction, which will be considerable if the two contiguous poles depart only a small distance from each other. These poles are therefore placed in the most favorable manner for determining the law of their repulsion at different distances ; for, as they cross each other in the points where the repulsion is the strongest, the other portions of free magnetism which are situated near these points will have almost the same effect upon the repulsion as if they were all concentrated at the point of intersection, so that we shall have nearly the reciprocal action of two points, each of which is charged with a constant and given quantity of magnetism of the same kind.

168. When, in the preceding experiment, the movable needle is separated from the fixed one, it will be drawn towards it, not only by the torsion, but also by the attraction of the terrestrial magnet, which tends to bring it back to the magnetic meridian. We must, therefore, begin by measuring separately this directive force for different distances, and afterwards add it to the observed torsion, in order to have the total effect of the repulsion of the two wires. The following are the particulars of an experiment, as made by Coulomb for this purpose.

Having taken two wires 24 inches long, and $1\frac{1}{2}$ line in diameter, he first put the horizontal one in its place, and by the method we have mentioned, determined the force with which the terrestrial magnet drew it back to the magnetic meridian. For this purpose, he turned the graduated circle twice round. The needle moved 20°, and therefore the torsion was 720°—20°, or 700°. We have before seen that when the same needle is deflected by small quantities from the magnetic meridian, its divergencies are proportional to the forces of torsion, exerted upon it. Making use of this result, we conclude that in order to deflect the horizontal wire one degree from the magnetic meridian, under the circumstances in which the preceding experiment was made, it is necessary to employ a force of torsion equal to $\frac{700°}{20°}$ or 35°. Coulomb now placed vertically

in this meridian another magnetic wire of the same dimensions with the first, so that if the two wires had been capable of coming in contact, they would have met at the distance of an inch from their extremities; but as their homologous poles were opposed to each other, the horizontal wire was repelled from the direction of its meridian, till the force of repulsion of the opposite poles was balanced by the combined forces of torsion and terrestrial magnetism, which tended to bring the horizontal wire to its point of rest. The following were the results of different trials;

Number of turns given to the suspending wire, by means of the graduated circle.	Observed angles of repulsion.
0	24°
3	17°
8	12°

The first experiment expresses the angle through which the movable wire was immediately driven, reckoning from the zero of torsion. When it stopped in this position, it was urged towards the zero by a force of torsion of 24°, plus the directive force of the terrestrial magnet for 24°, namely, 24 × 35°, or 840°. The total repulsive force was therefore 864°.

In the second experiment, the graduated circle was turned three times in a direction contrary to the 24° first produced; but in spite of this great torsion, the movable wire, repelled by the fixed one, was deflected 17° from its magnetic meridian; so that the force of torsion was then 3 circles + 17° or 1097°, and adding to this the directive force for 17°, which is 17 × 35°, or 595°, we obtain for the total repulsive force 1097° + 595°, or 1692°.

In the third experiment, the wire was twisted through eight circles. The magnetic wire stopped at 12° from its magnetic meridian; and therefore the torsion was eight circles + 12°, or 2892°, to which adding the directive force, or 12 × 35° = 420°, we have for the total repulsion 3312°.

In these experiments, therefore, when the arcs of repulsion are sufficiently small, so that they may be reckoned equal to their chords, the distances were 12, 17, 24; and the corresponding repulsive forces, measured in degrees of torsion, 3312°, 1692°, 864°.

From these results it appears that the repulsive force diminishes as the distance increases, and that it diminishes more rapidly than in the ratio of the distances simply; for the third distance 24, is double of the first, and the repulsive force 865, is much less than half of 3312. Let us try, therefore, the inverse ratio of the square of the distances; and by setting out from the first force 3312, they ought to be $3312 \frac{(12)^2}{(17)^2}$, and $3312 \frac{(12)^2}{(24)^2}$, or 1650, and 828, instead of 1692°, and 864, as obtained by experiment. The differences 42° and 36° correspond nearly to an error of one degree in the observed positions of the movable steel wire, since the directive force is 35° for each degree of deviation from the magnetic meridian. Neglecting, therefore, this error, which we may consider as very small in experiments of this kind, we conclude that the reciprocal action of two magnetic wires decreases as the square of the distance increases; and, consequently, that magnetisms of the same kind, by which this action is produced, repel each other according to this law.

The small deviation which we have found between the observed and calculated repulsions does not perhaps arise from an error in the experiments, or any want of exactness in the law which we have deduced; for the experiment is made, not upon magnetic points, but upon portions of the wire of a certain extent, the configuration of which has an influence upon the results. In the last experiment, indeed, where the two wires were nearest each other, the influence of the points lying near the intersection was more weakened by obliquity than in the other experiments; or, in other words, there were at equal obliquities more points which acted in the case of the greater distance than in that of the smaller. But as we did not take this augmentation into account, we ought to find that the repulsive force, observed at the smallest distance, on being reduced in the ratio of the square of the distance, gives, for the larger distances repulsive forces a little more feeble than those which were actually observed.

169. The same experiment repeated with poles of an opposite name, shows that they attract one another in the inverse ratio of the square of the distance. This law of attraction and repulsion is the same in magnetism as in electricity.

170. It follows from these results, that Coulomb has legitimately omitted in his experiments the action of the distant poles; for as the needles were two feet long, the greatest arc of repulsion which was 24 degrees, corresponded to a distance of 5 inches between the poles which were directed toward each other; and consequently the other poles were at least four times as distant from those which were directed toward each other, as these poles were from one another. Their direct action consequently, was at least sixteen times weaker; and it was even still more reduced by the extreme obliquity of the direction in which it was exerted. The case would not be the same if the experiment had been made with shorter wires. It would then have been necessary to take account of the reciprocal action of these two poles, and the length of lever by which each of them acted; this would lead us into complicated processes which are avoided by employing longer needles.

Of the Intensity of Free Magnetism in each Point of a Needle Magnetized to Saturation by the method of Double Touch.

171. Having found infallible methods for developing, in bars of iron and steel, all the magnetism which they can acquire, and for preserving it in a durable manner, we shall now determine experimentally the magnetic state of each of these points.

For the sake of simplicity, we shall begin with the case of a cylindrical steel wire *AB*, of a very small diameter, and regularly Fig. 116
magnetized by the method of double touch. The development of magnetism will then be perceptibly equal, but of an opposite nature in its two halves, and will decrease rapidly in each of them, from the extremity towards the centre. If, therefore, we erect at different points of the wire, perpendicular ordinates, to represent the intensity of free magnetism, whether boreal or austral, these ordinates will commence by being nothing at the centre, from which they will go on increasing equally and slowly on the two sides. At a certain distance they will increase rapidly towards the extremities of the wire, where they will reach their maximum. This is all our experiments permit us to conjecture.

In order, however, to determine the value of these ordinates, we
Fig. 117. must suspend by a single fibre of silk, a small trial needle *a b*, previously magnetized; and after having allowed it to place itself in the magnetic meridian, we must present to it, in the same meridian an opposite pole of the wire *AB*, held vertically at a small distance from the pole *a*. This operation will not change the direction of the needle *a b*; but if we make it deviate, in the least degree, from its meridian, it will return to it more rapidly than if the wire did not act upon it, because it is drawn back by the combined action of the earth and the wire. The first of these forces may be easily measured, by making the needle oscillate by the sole influence of terrestrial magnetism; it will be proportional to the square of the number of oscillations performed in any given time, as a minute. If we afterwards observe, in the same manner, the number of oscillations, which the needle performs, when acted upon, both by this force, and by that of the wire, we shall obtain, in like manner, by squaring this number, the total action which it experiences; and by subtracting the first square, depending on the terrestrial magnetism, we shall have a separate measure of the action exerted by the wire. But in this case, the point *M*, situated opposite to the needle, will have the most powerful effect, both because it is nearest to the needle, and because it attracts it directly in the horizontal plane in which it oscillates; whereas, the other points, situated above and below it, act at a greater distance, and with a greater obliquity. The influence of these two causes, indeed, is very feeble for the points of the wire which are near *M*; but, if the action of one of these points is stronger than that of *M*, that of the point situated on the other side, at the same distance, will be weaker by nearly the
Fig. 116 same quantity; for, whatever be the nature of the curve *A′ C B′*, which joins the different ordinates, we may always, when we consider a small portion of it, substitute the straight line which touches it. In virtue, therefore, of this substitution, half the sum of the equidistant actions exerted by the points near *M*, will differ very little from that of *M*; and therefore it follows, that in each experiment, the part of the wire whose action is most energetic, will exert a total force, almost exactly proportional to that of the point *M*, and consequently to the quantity of magnetism which exists in a state of freedom. This proportionality, however, must not be ex-

tended to the extremity of the wire, nor even to its immediate vicinity; for then the points situated beyond the wire become so near, that their absence is sensibly felt; and consequently, the action experienced by the trial needle cannot be the same as if the wire were continued. When the needle oscillates, for example, before the extremity *B* itself, the force which urges it is only one half of that which would have acted upon it, if there had been, in the prolongation of the wire, another equal wire; and consequently, the observed forces will be nearly one half of those which would have been obtained, if the needle had been continued with the law of magnetism which it possesses. In order, therefore, that the results observed in this case may be compared with those which the needle presents when it oscillates before the other points, where the wire acts upon it both from above and below, it will be necessary to double the number which represents the square of the oscillations. This is what Coulomb himself did; and Biot satisfied himself by an exact calculation, that this correction was very near the truth.

172. It is necessary here to notice an objection which may now naturally present itself. When we determined the law of magnetic attraction and repulsion at different distances, we supposed that all the magnetism of the same pole acted entirely in the horizontal plane of the movable needle, as if it were nearly concentrated in a single point; whereas we have now said, that the action of the different points of this pole, which are above and below the plane of the needle, will be greatly weakened by the obliquity. The reason of this is, that, in these two cases, the distance of the movable needle from the fixed wire is very different. In the preceding experiments the pole of the movable needle was always removed to a considerable distance from the fixed needle, compared with the space over which the free magnetism was distributed. In the present case, on the contrary, this space is considerable, relative to the distance of the small needle, which is very near the wire. This modification renders the influence of obliquity much more considerable. The action of the points situated above and below the plane of the trial needle, decreases, therefore, with much more rapidity. The total action is always nearly the same as if the wire were continued indefinitely on both sides of the plane of the needle, and with the same magnetic intensity which resides in the point that is actually

before it. Hence we see why the action thus observed is sensibly proportional to the quantity of free magnetism which exists in this point.

In making these experiments, two important precautions are necessary. The first consists in employing wires so long, that in observing the action of one of their extremities upon the needle, there may be no occasion to take account of the action of the other extremity. The second precaution is, that the needle, though small and easily moved, may also be so strong, and made of steel so hard, that its magnetism shall not be perceptibly modified by the action of the wire; for if this change take place, the experiments made before different points would not be comparable, since the part of the action which depends on the needle would vary. This actually happened to Coulomb in his first experiments, when he employed a small needle two lines long, and placed at the distance of three lines from the wire. This needle, abandoned to the sole action of the terrestrial magnet, gave very feeble indications of magnetism; but when it was placed at the distance of three lines from the wire, its magnetic state increased considerably, and by presenting it to each extremity of the wire, it suddenly changed its poles.

Warned by these phenomena, Coulomb employed a more powerful trial needle, which was three lines in diameter, and six lines in length. The diameter of the magnetic wire was two lines, its length 27 inches, and its weight 865 grains per foot. In order that it might not produce any change in the needle, he held it at a greater distance, namely, 8 lines, and measured the number of oscillations which it performed in a minute, when it was held before different points of the wire. Having previously observed the number of oscillations which it performed in the same time by the single action of the terrestrial magnet, the difference between the squares of these numbers expressed, in each experiment, the reciprocal action of the wire and the needle; an action which, as we have already said, must be nearly proportional to the intensity of free magnetism in the point of the wire before which the needle oscillated. By placing these results upon the corresponding abscissas, Coulomb obtained the curve of intensities represented in figure 118. The ascending form of this curve confirms all that the preceding experiments have led us to anticipate respecting the distribution of free mag-

netism, and the great intensity of its development towards the extremities of the bar.

173. Coulomb repeated the experiment with the same wire, having changed only its length, all other circumstances remaining the same. He then found, that whatever this length be, provided it exceeds 6 or 7 inches, the three first and the three last inches give always nearly the same results as a wire 27 inches long; so that the intensity of free magnetism is sensibly the same, from the extremity of these wires, to a distance of three inches; after which it becomes equally weak and insensible in all of them; or in other words, the curve of intensity is merely transferred to the extremities of the wire, without changing its form in this part, and it is only after having descended near the axis, that its ordinates begin to remain nearly constant for a greater or less space so as to become nothing at the centre. This constancy in the extreme ordinates for all wires of the same kind and of the same size, indicates clearly that the free magnetism received in this part a degree of development which it could not exceed, a result perfectly conformable to the idea which we have given of the state of saturation. Coulomb found less constancy in the small ordinates of the curve near the middle of the wire, and he even ascertained, that in very long wires these ordinates varied accidentally, sometimes passing from positive to negative; a result easily understood, if we consider that all these inversions constitute so many possible states of equilibrium, and that the slightest circumstance, such as a contact more or less prolonged during the process of magnetizing the wire, or even the action of the poles of the wire itself upon its centre, is sufficient to develope them.

In considering the curve of intensity, as traced by Coulomb, it is easy to see that it results from the combination of two curves, called by geometers logarithmic, which, setting out from each extremity of the magnet, have their ordinates equal, and in opposite directions, as shown in figure 119. The variations, indeed, of the intensities calculated in this manner for different distances from the centre of the wire, is found perfectly conformable to observation. This law, considered analytically, indicates a distribution of free magnetism exactly similar to that of the two electricities in insulated electrical piles, when the absorbing action of the air has equalized the tensions

of their poles; and this is indeed what we ought to expect, from the perfect analogy which we have remarked from the beginning between magnets and poles of this kind. The formulas deduced from this approximation enable us to trace the variations of the magnetic charge in wires of the same magnitude, but of unequal lengths, and in wires of the same length but of unequal magnitude; and, in short, in wires of any magnitude and length whatever, by supposing them always magnetized by the method of double touch. The conclusion derived from a comparison of the calculated and observed results cannot, however, be explained here; but the reader will find it in Biot's *Traité de Physique*.

174. The experiments of Coulomb, upon which these calculations are founded, present an equal and opposite distribution of magnetism in the two halves of the needle; a distribution which is indeed the most advantageous for obtaining a considerable directive force, and which, therefore, we should endeavor as much as possible to effect. Experience, however, informs us that this is impossible in tempered needles, when their length is very great, compared with the diameter of their transverse section.

In this case, whatever method of magnetizing is employed, several centres are formed, the development of which is probably owing to the reaction of the poles upon the points near the centre. In this case, the curve of intensity is no longer situated for the two halves of the needle on different sides of the axis. It necessarily undulates above and below, as represented in figure 120; and, consequently, its form can no longer be represented by the same analytical expression as before. Fortunately, there is every reason to believe that this limitation is not to be regretted. For, in the first place, it does not happen in annealed needles, unless, perhaps, they very much exceed in length those which are ordinarily used; and with respect to tempered needles, if we are not constrained by some urgent motive to make them extremely light, there will always be an advantage in giving them a sufficient thickness, in order that the free magnetism may be of the same nature in each of their halves; for, with an equality of coercive force, the development of new centres always weakens the statical moment of the directive force for each half of the needle, and renders the action less energetic at equal distances from the poles.

It is obvious, in general, that the distribution of magnetism in a needle, and the absolute degree of saturation of which it is susceptible, depend not only on its dimensions, but also on the higher or lower temper which it has received. Coulomb had studied the influence of this last circumstance. He shows that we must always begin by tempering the needle at a white heat, whatever be its dimensions, and then, if its length is less than thirty times its thickness, we must leave it at this temper; but if it exceeds this proportion, we must bring it back again, by annealing it to the state of dark red, in order to avoid a multiplication of centres which its great length might occasion.

Of the Size and best Form of Compass Needles.

175. The results at which we have arrived in the preceding sections, should serve to direct us in making needles for compasses. Although this application may be very easy, its importance entitles it to particular attention; and this will be the more readily bestowed, as here also Coulomb is our guide.

The compasses commonly used, whether designed for land or sea, are formed of needles artificially magnetized, and provided with a cap at the centre, which rests on a pivot of some metal not magnetic. A little counterpoise placed on one arm of the needle renders it horizontal. It is necessary to change the place or size of this counterpoise as we change our latitude, the moment of the vertical forces of terrestrial magnetism being different in different latitudes. Whatever be the form of the needle, it is easy to determine, on its surface, the horizontal direction of the magnetic resultant by the method of reversal. If the needle move on its pivot with perfect freedom, it will naturally direct itself in such a manner as to cause the magnetic axis to correspond exactly to the magnetic meridian; and consequently, when once known, it will exactly determine this meridian. But the friction of the pivot on the bottom of the cap opposes this tendency, and presents an obstacle which the directive force must surmount in order to bring the needle to the magnetic meridian; whence it is evident, that the best con-

struction is that in which the friction is least, and the directive force the greatest.

176. On the supposition that the pivots and caps are of the same shape, the same materials, and formed with equal care, the friction will depend simply on the weight of the needle; and it may be measured by presenting the needle from a distance, while balanced on its pivot, to a magnet that draws it from the plane of the magnetic meridian, and observing how nearly it returns to its proper situation, when left at perfect liberty. It should seem that the arcs which it describes on each side of this plane, a great number of experiments being used, should be proportional to the force of friction. By observations of this kind Coulomb found that for very sharp pivots, and caps formed of a substance sufficiently hard, the friction is proportional to the power $\frac{3}{2}$ of the pressure.

But when by long use the pivots have become blunted, and as it were fitted to the excavation of the cap, which is frequently the case, he found the friction to be simply proportional to the pressure. This is the first established fact of which we are to avail ourselves. Let us conceive a magnetic needle of any form and size whatever, placed on a pivot of the above description; and, without changing its length at all, let us only double its thickness, or which amounts to the same thing, cover it with another lamina of metal precisely similar; the pressure on the pivot will be doubled, and also the friction; but not the directive force. For it is manifest, and proved by experiment, that this force increases in a less ratio than the thickness, since the re-action of homologous poles on each other destroys a part of the free magnetism which each one separately possessed. The needle, when covered with its additional coating, will point out the magnetic meridian less accurately than before; and hence it will be seen that, other things being the same, the most correct needles are those of the least diameters. The diameter will be sufficiently great if it be such as to prevent the needle from being bent by its weight.

177. Let us now proceed to consider the lengths of needles, and first, the case of those which from their dimensions and physical state possess only one kind of free magnetism in each of their ends. Then the analytical law relative to the intensities, obtained above, shows that unless the needles are exceedingly short, their

directive forces, the diameters being equal, are proportional to their lengths, at least if we suppose their transverse sections to be every where the same. But, in this case, the weight, and consequently the friction which results from it, are each proportional to the length. So that if we avoid exceedingly small dimensions, all needles, whatever be their lengths, have nearly the same degree of accuracy. This, however, is true only on the supposition of a symmetrical distribution of magnetism in the two arms of the needles, and a freedom from consecutive points. It is necessary then to attend to the relation of the length to the thickness, as well as to the state of annealing and tempering, in order that this condition may be fulfilled; and we must accordingly observe the directions given in the preceding section. If the length of the needle be less than 30 times its thickness, we must temper it at a white heat, before we develope its magnetic power. If, on the other hand, its length exceed this proportion, we must anneal it till it becomes of a dark red color. When the length is between these two limits, it is not of much consequence which process we employ. The superiority possessed by needles having a single magnetic centre over those of several centres is incontestible, if we suppose the same quantity of magnetism to be developed on the whole in each case. But it is not impossible, that with other proportions of thickness and length, and other degrees of temper, the diminution of magnetic force occasioned by the multiplicity of centres, may be compensated by the existence of a coercive force more considerable than could be otherwise obtained, or by a more abundant development of magnetism. It appears that Coulomb performed a great many experiments relative to this subject, which he proposed to arrange in tables, so that we might know beforehand what were the most favorable circumstances for every variety of dimensions in the needles. But unfortunately, nothing has been found in his manuscripts sufficiently matured to be employed in so important an undertaking; and the subject still demands the attention of philosophers.

178. It now remains for us to inquire, which is the most advantageous of all the forms of needles. Uusually, they are parallelograms, cylinders, or arrows. Coulomb ascertained by experiment, that when the weights are equal, arrow-shaped needles have the greatest directive force. And this might be naturally inferred from

the reason which induced him to arrange his magnetic bundles by steps retreating in the direction of their thickness, as already explained. It will also be evident from the same principles, that there is great disadvantage arising from the extremities of the needles being enlarged; and this modification, which some have proposed to introduce, should be steadily opposed. The remarks here made are equally applicable to dipping needles.

179. Mariner's watches or chronometers, employed to measure time on board of vessels, having in their construction several pieces of steel, some of which are movable, must evidently be subject to variation in their rate of going, if placed in the vicinity of magnetic bars. This is proved by experiment. Consequently the same effect must take place to a certain degree at sea, both on account of the continual action of the earth, and the magnetic influence of the ferruginous masses, by which compass-needles are deflected. For the safety of navigation, it is very important to diminish as much as possible these changes in the rate of going to which chronometers are liable; and it may undoubtedly be effected, in a great measure, by placing them always in the same place, and as far as possible from compass-needles and magnetic bars. With this precaution, their variation will be very small, and nearly constant; so that corrections may be easily applied by means of astronomical observations. This important discovery was made in England a few years since.

The quantity and vicinity of iron in most ships, has an effect in attracting the needle. For, it is found by experience, that it will not point in the same direction when placed in different parts of a ship; also, it is rarely found that two ships steering the same course by their respective compasses, will go exactly parallel to eaoh other, yet these compasses when compared on board the same ship will agree exactly. Owing to the changes which have taken place in ship-building, this error was much smaller formerly than it is now. It is only within a few years that pig-iron has been employed for ballast, the weight of which, in some vessels, exceeds three hundred tons. An immense surface of iron is also introduced by the admirable invention of iron tanks to supply the place of the old water-casks. Moreover, the knees, sleepers, and sometimes even the riders, are now of iron; and some attempt has recently been made

to employ gun-carriages of the same material. But of all innovations of this kind, the invention of the patent capstan by Captain Phillips, is that which, from its form and situation, has the greatest effect on the compass. Mr. Barlow has attempted to neutralize this disturbance by a correcting plate, represented in figure 191. This plate may be so placed in regard to the needle, as to counteract exactly the action of the ship.

Of the Action of Magnets on other Natural Substances.

180. We have said that iron, steel, nickel, and cobalt, were the only magnetic metals at present known. And indeed they are the only metals capable of acquiring a high and permanent degree of magnetism. Still if we take a small needle a third of an inch in length, and of about one fiftieth of an inch in thickness, of any substance whatever, and suspend it by a silk thread between the opposite poles of two powerful magnets, as represented in figure 121, it will be found always to place itself in the direction of these poles; and if we cause it to vibrate about its line of equilibrium, the oscillations performed in presence of the magnets are much more rapid than those which take place in empty space. These little needles then are sensible to the influence of magnetism. We shall be equally successful whether we employ in our experiments needles of gold, silver, glass, wood, or any other substance, organic or inorganic. These remarkable facts were discovered by Coulomb, and announced by him to the National Institute in May, 1812.*

181. There seem to be only two ways of accounting for these phenomena. Either all substances in nature are susceptible of magnetism, or all possess particles of iron, or some other magnetic metal from which this property is derived. But this alternative is not so necessary as we should at first suppose; for it rests on the assumption, that the action exhibited by the needles in question is actually magnetic; and this cannot be positively affirmed. When we find that the simple contact of heterogeneous bodies developes very sensible electric forces, whose very existence we had never

* A detailed account of them is given in Biot's *Traité de Physique*, with a calculation of the forces exerted by them.

before suspected, must we not regard it as possible, that other circumstances are capable of developing like or analogous forces, whose feeble effects can only be perceived by means of the most delicate instruments; and may not the action observed in the little needles of Coulomb be referrable to some subtle force with whose nature we are yet wholly unacquainted? These questions cannot be answered in the present state of the science. The method of oscillations, which Coulomb employed, and which we have explained, is the most delicate and simple of all known means of discovering the presence of iron in the products of nature and art, even when it exists in exceedingly small quantities. We have only to form needles of the substance which we would examine, to make them oscillate between two powerful magnets, and to compare their oscillations with those of needles made of iron combined with some other substance not magnetic, the relative proportions of the iron and the unmagnetic substance being known.* And by this method we can not only discover and measure exceedingly small quantities of iron in its metallic state, but even when it is in the most intimate combination with oxygen and other substances. I will illustrate this remark by an example. Among those minerals which have been referred to the class called mica, there is a great number whose chemical properties are exceedingly different; and the laws of the polarization of light, applied to these substances, denote very different crystalline structures. In the course of his inquiries, relative to this subject, an account of which is contained in the Memoirs of the Academy of Sciences for the year 1816, Biot was led to compare two specimens of mica, one of which was brought from Siberia, and the other from Zinwald in Bohemia, the latter being mixed with crystals of tin. Although the lamina of these two specimens of mica were very transparent, chemical tests applied to them, indicated the presence of oxide of iron, but in very different proportions. The Zinwald mica contained by far the largest quantity; according to the exact analysis of M. Vauquelin, the oxide of iron made 20 hundredths of it weight. Proceeding to analyze the other mica, the method of trying both by means of magnetism suggested itself

* For the formulas necessary for this purpose see Biot's *Traité de Physique.*

to Biot. He then cut a number of small rectangular plates of mica of equal dimensions, and fastened them parallel to each other in bundles; and having made these bundles oscillate successively between two powerful magnets, suspending them by flattened silk threads, whose torsion was wholly imperceptible, he found that the bundle of Zinwald mica made 12 oscillations in 55″, while the other bundle made only 7 in the same time. The magnetic forces then were as the squares of these numbers, that is, as, 144 to 49. Now, if we consider these forces as proportional to the quantities of combined oxide of iron, we shall see, that if the Zinwald mica contains 20 hundredths of this oxide, the other mica must contain $\frac{20.49}{144}$ or 6,8. And the result of the chemical analysis to which Biot had recourse after this experiment, gave this proportion exactly. I do not doubt that, in most cases, this kind of test would be found equally useful, and that it would lead to curious results respecting the intensity of the combination of iron with other substances; as to its accuracy it cannot be called in question, after the experiments of Coulomb, as above stated; and no one can make use of this method without being convinced of the truth of what is here advanced.

Of the Laws of Terrestrial Magnetism in different Latitudes.

182. We have observed, that the inclination and declination of the needle and the intensity of magnetic forces are each different in different parts of the earth. The processes necessary for determining these phenomena have been partially explained. We have only to carry a magnetized needle to the different places to be examined, or to employ several needles capable of being compared with each other, and to observe the three particulars above mentioned. Experiments of this kind were performed about the year 1700, by the celebrated Dr. Halley, to whom the English government entrusted a vessel destined to the purpose of transporting him and his instruments to different regions of the globe. But the researches of Dr. Halley being directed chiefly to the determination of the longitude by the declinations of the compass needle, he confined himself principally to observations of this kind, which unfortunately are most

liable to change; so that when we now have occasion to speak of the state of terrestrial magnetism, it is necessary to have recourse to the disconnected observations of more modern navigators. But the needles used in these cases being exceedingly different, as well as the methods of taking observations, it is evident that the results must be crowded with seeming anomalies, so that at best we can only expect to find confirmations of the most general facts belonging to this subject, without being able to enter much into detail. In fine, what increases the difficulty, is the entire absence of observations throughout a great part of the globe, where they are the more needed, as a multitude of facts seems to indicate in those parts the action of very remarkable local causes, which we are unable to form any conception of, without the aid of observation. The unusual degree of attention which the subject of the earth's magnetism has received within a few years promises soon to supply the deficiences of observation.

183. I will now consider the difference of magnetic inclination in different parts of the earth, because this phenomenon seems to vary with the time much less than the declination. To discover any law relative to the inclination, the point first to be attended to, is to ascertain the parts of the globe where it is nothing; that is, where a needle, which, before being magnetized, rested in a horizontal position, would remain horizontal, after being magnetized. A series of such points being connected would form on the surface of the earth a curved line, called the *magnetic equator*, and which all authors have hitherto considered as a great circle of the earth, inclined to the terrestrial equator at an angle of about 12°. Such in reality is the form which the numerous observations made on the portion of the magnetic equator, comprehended by the Atlantic ocean, seem to point out. This portion, being on the route of European vessels destined for America and India, has been more frequently observed than any other. The great circle indicated by these observations would cut the terrestrial equator at two points or *nodes*, one of which, the most western, would be situated at about 113° 14′ of west longitude from the meridian of Greenwich; that is, in the South Sea, near the island Gallego, at the distance of nine hundred leagues from the coast of Peru; so that the opposite node would be at 293° 14′ of west longitude. Such has been hitherto

the prevailing opinion. But the above particulars are entirely erroneous, so far as regards all those parts of the South Sea, situated above the west node, between 113° and 268° of longitude, comprehending, in fact, nearly a hemisphere of ocean. By examining the observations made with the utmost care by William Bayly and Captain Cook, in two separate vessels, employed in 1777 to navigate the South Sea, it will appear that they have each fixed the magnetic equator at 156° 30′ 9″ of west longitude, and at 3° 13′ 40″ south latitude; whereas, by continuing the great circle, indicated by observations made in other parts of the earth, this equator should have a north latitude of 8° 56′ 30″. It hence appears that the magnetic equator, after meeting the terrestrial equator at about 113° of west longitude, descends again in a southerly direction; and, as has been shown by the observations of Bayly, confirmed in this particular by those of Dalrymple, that there is no inclination in the China Sea, at about 7° of north latitude and 254° of west longitude, we must conclude that between this longitude and that of 156° 30′ west, as determined by the observations of Cook, the magnetic equator cuts the terrestrial equator at least once; and this makes it necessary to suppose that it cuts it a second time, near the eastern coast of Africa, since we find it again in the Atlantic ocean, with a south latitude. So then there are at least three nodes, and perhaps four, if the magnetic equator, about its western node, ascends a little towards the north before descending to the south near the archipelago of the Society Islands. The situation of these nodes, and the true form of the line of no inclination between them, have been very ingeniously interpolated by M. Morlet; and we hence arrive at the curve represented in plate IV.

184. This curve cuts the terrestrial equator for the first time, at about 18° of east longitude, reckoned from the meridian of Greenwich, on the western coast of Africa. Thence keeping a westerly direction it descends to the south of the equator, from which it continues to depart, until it has reached 14° 10′ of south latitude, this limit being at 26° of west longitude; it then becomes for a short space nearly parallel to the terrestrial equator. But leaving this maximum, it gradually ascends towards the continent of America, until it reaches a point of about 96° of longitude, one hundred and twenty leagues to the west of the Galapagos Islands, in the Pacific

Ocean; here we again find it very near the equator; but then the curve is inflected, becoming more and more nearly parallel to the equator, and instead of cutting it, it approaches so as just to touch it at about 118° of west longitude; after which it descends again to the south, until at 161° it reaches a second maximum of south latitude, of about 3° 15′, on a meridian nearly intermediate between the archipelago of the Friendly and that of the Society Islands. On leaving this point it descends gradually towards the north, and cuts the terrestrial equator at 184° of west longitude, or 176° of east longitude, not far from the meridian of the Mulgrave Islands; then continuing its progress to the north, it reaches its first maximum of northern latitude, at about 130° of east longitude, near the meridian of the Phillipine Islands, where its distance from the equator is about 9°; thence it approaches somewhat nearer the equator, and attains a minimum at about 108° of longitude, at the entrance of the gulf of Siam, a little to the south of the Isle of Condor, where the latitude is not more than 7° 44′ north. It soon begins to ascend again in a northerly direction, traverses the bay of Bengal, cuts the southern extremity of India; and returning to the northern hemisphere reaches its absolute maximum of northern declination from the equator, namely, 11° 47′, in the Arabian Sea at 64° of east longitude. Descending now toward the equator it cuts the eastern coast of Africa a little to the south of the Straits of Babelmandel; and traversing the interior of the continent to the eastern coast, it returns to the point of the terrestrial equator from which we began to trace its course. A new determination was made of this line for 1835 by Duperrey.

185. The magnetic inclinations, observed on each side of the line which we have traced, are found to increase as we depart from it. If we confine our attention to that part of the globe where the magnetic equator seems to be nearly circular, which comprehends Europe, the Atlantic Ocean, and the eastern coast of the American continent, it will be seen that the inclination remains nearly constant on parallels situated at equal distances on each side of this equator; so that according to this law the maximum of inclination would be in two opposite points of the earth, the northernmost of which would be found in 23° west longitude, and 90°—14°, or 76° north latitude; while the other, diametrically opposite, would

be situated in 203° of west longitude, and 76° of south latitude. These then would be the poles of the magnetic equator, if this equator were circular; and the dipping needle would in these places be vertical. But this is not conformable to the fact; for the voyages of discovery, recently undertaken by the English in the northern regions, furnish different results; very considerable inclinations, exceeding 84°, were observed in longitude 61° and latitude 75°; but the declinations, which amounted to 87°, were still western, as at London. Whence it appears, that the true magnetio pole is further towards the west than the preceding conclusions would seem to indicate. As the line of no inclination is called the magnetic equator, though it is not a great circle of the earth and does not indeed lie in the same plane, so we might suppose lines to be drawn through all those places where the inclination of the north or the south end of the needle is the same, and these lines would be magnetic parallels; the magnetic latitude of a place being its distance from the magnetic equator. Such lines are drawn on magnetic charts and called isoclinal lines.

186. As, in our inquiry respecting the magnetic inclination, our first object was to find the series of places where it is nothing; so in examining the phenomena presented by the declination, we must begin by determining the points on the globe where it is nothing, and which continued would form a curve called the *line of no declination*. These lines do not take the direction of geographical meridians; they are, on the contrary, very oblique to these lines, and they present very irregular inflections. According to the latest observations, there is now a line of no declination in the Atlantic Ocean between the old and new world. It cuts the meridian of Paris at about 65° of south latitude; thence it ascends to the northwest, about 33° of longitude, where it may be traced on the heights of the coast of Paraguay; after which, acquiring again a direction nearly north and south, it passes along the coast of Brazil, and thus reaches the latitude of Cayenne. But then suddenly shifting its direction to the northwest, it directs itself towards the United States, and thence towards the other northern parts of the continent of America, which it traverses without altering its direction.

187. This line is not fixed on the globe; at least for a century and a half, it has had a considerable motion from east to west. In

1657, it passed through London, and in 1664 through Paris;* so that according to its present direction, it has traversed on the parallel of latitude of Paris more than 80° of longitude, in the course of 180 years. But it seems evident, that this motion is not uniform; it is even unequal on different parallels; for, in the Antilles, for example, the declination has scarcely undergone any change for 140 years. And, in general, when we consider how very slow this motion is, we are not by any means certain that it is always progressive, or that it will continue in any particular direction. The very careful observations which have been regularly made in the observatories of England and France, have seemed to indicate, for some years, the commencement of a retrogradation towards the east; but a like retrogradation was observed in the years 1790 and 1791, which did not continue. Time only can make us fully acquainted with these phenomena.

There is another line of no declination, nearly opposite to the one just described; this, constantly directing itself to the north-west, takes its origin in the Southern Ocean, cuts the western extremity of New Holland, traverses the Indian Ocean, strikes the continent of Asia at Cape Comorin, and thence traversing Persia and the western part of Siberia, ascends towards Lapland. But what is very remarkable, this line becomes forked near the Asiatic archipelago, and gives rise to another branch which, directing itself almost exactly north and south, passes through this archipelago, traverses China, and enters the eastern part of Siberia. The two branches which proceed from this line, either have no motion, or an exceedingly slow one. It seems that there has been no sensible change in the declination at New Holland for the last 140 years.

Traces of a fourth line of no declination were observed by Cook in the South Sea, near the point of the greatest inflection of the magnetic equator. Navigators have not followed these indications of the line to the northward, but it is extremely probable that it is continued; for, as has been very justly remarked by M. de Humboldt, since the declination changes its algebraical sign from west to east, or from east to west, in passing from one side of each line of no declination to the other, it is necessary, taking in the whole

* See note on the declination of the magnetic needle at London, &c.

globe, that the number of lines of no declination should be equal, so that after all the changes from plus to minus and *vice versa*, we return to the sign from which we set out

188. Having determined the direction of the lines of no declination, it is necessary in order to limit these phenomena in another respect, to enumerate the places where this declination is greatest. With respect to this particular also we discover very irregular lines, which fall between those just mentioned. The greatest declination observed in the southern hemisphere by Cook, was at 60° 40′ of latitude, and 91° 25 of west longitude from the meridian of Greenwich; this was 43° 45. In the northern hemisphere as we can approach much nearer to the magnetic pole, a much greater declination has been observed, in some cases approaching to 90°. Such are those observed in the English expeditions to the north pole. The numerous compass needles, which in our climate direct themselves towards the north were here turned to the west. They ought even to direct themselves to the south if we pass the magnetic pole; and the direction of the needle would become wholly indeterminate upon arriving at the pole itself, the resultant of magnetic forces being then vertical, its horizontal element would be nothing. In general, it is evident from this reasoning, that the horizontal directive force must be quite feeble in places where this inclination is very great; so that if the smallest foreign force intervenes, whether of the ferruginous substances situated near the earth's surface, or of the iron used in the construction of vessels, it must exert a very decided influence over the compass needle, and almost entirely neutralize its directive power. Such is undoubtedly the explanation to be given of those singular and unexpected variations and irregularities, which take place in the direction of needles in high latitudes, as formerly observed, and now more recently by the English. Lines are drawn on magnetic charts, which pass through all those places on the earth where the variation of the needle is the same. Such lines may be regarded as magnetic meridians, though not symmetrical as the geographical meridians. They are commonly called isogonal lines.

189. After having thus related all that is at present known on the subject of the direction of magnetic forces in different parts of the earth, it only remains to consider the absolute intensity of these

forces. This subject till within a short time has been much less studied than that of the declination and inclination; undoubtedly on account of its being attended with more difficulty. The first correct observations on the intensity were made by M. de Humboldt, in his extensive travels, and by M. de Rossel, in the expedition of Admiral Entrecasteaux. Very valuable information relating to magnetic intensity may be learned from Captain Freycinet's voyage round the world, and from the English expeditions to the North Pole.

We are indebted to MM. de Humboldt and de Rossel, for the discovery of a very remarkable phenomenon already referred to, namely, the general increase of magnetic intensity as we proceed from the equator towards the poles.

The same compass needle which, at the departure of M. de Humboldt, made at Pars 245 oscillations in 10 minutes, made at Peru only 211, as we have already mentioned; and it has always been found that the number of oscillations diminishes as we approach the magnetic equator, and increases as we depart from it north or south. We cannot attribute these differences to a diminution of magnetic force in the needle, nor can we suppose that it is materially affected by time or heat; for in the case of M. de Humboldt's needle, after having remained three years in the hottest regions of the earth, it gave a second time, at Mexico, oscillations as rapid as at Paris. In fine, M. de Humboldt has spared no pains to render his observations accurate; and they are confirmed by the results obtained from making needles oscillate successively in the magnetic meridian, and a plane perpendicular to this meridian. Indeed, the inclination deduced in this way is found by M. de Humboldt to accord with that obtained by direct observation, although he was not at the time aware of the relations subsisting between his elements which M. Laplace has since pointed out. As the accuracy of these observations cannot be called in question, we must also give our assent to the consequence which results from them, namely, that the increase of magnetic terrestrial force is constant from the magnetic equator to the poles. The experiments, made by M. de Rossel at Brest and in New Holland, also lead to the same conclusion. A great many observations have been made within a few years on this element of terrestrial magnetism, and lines

are now drawn on the magnetic charts, passing through all those places where the magnetic intensity is the same. Such lines are called isodynamical lines.

190. Suppose now a globe to be taken and covered with the three great classes of lines which represent the three elements of the earth's magnetism, such a chart, however accurately executed, could only represent the *mean* value of these elements for a single epoch. For we have had occasion in sketching the line of no declination to remark upon the constant change which has been observed in its position since the earliest magnetic records. It is now time to add, that the value of each one of the elements, at every place on the planet, is subject to variations of longer and shorter periods, and sometimes to irregular fluctuations of great amount. A daily and yearly period have already been sufficiently established. A secular period of indeterminate length is also clearly deduced from the facts of the case. The whole subject of terrestrial magnetism is in process of a severe and extensive examination. Magnetic observatories have already been established in various parts of the world, which compete even with astronomy in the accuracy and perseverance with which the observations are conducted. The opinion of the earlier observers in regard to the daily and yearly changes has been fully confirmed, and the hope is profoundly entertained, that when the elements and the changes of the elements are carefully determined and expressed in empirical laws, the time will have come for entering with success upon a Theory of Terrestrial Magnetism.

By referring to Note III it will be seen that the needle reached its greatest western declinatioon at London in 1814, or 157 years after it was observed by Bond to point due north. Since 1814 it has been moving slowly westward. If it take as many years to return, as it did to proceed westward, it will reach the point of no declination in the year 1971. Should it go as far to the eastward as it did westward, and take as long a time, it will reach the easternmost declination in the year 2128, and the total arc of declination will be 48° 35′ 48″, the period occupied in traversing it being 314 years. The average annual variation would be 9′ 17″. But it is much smaller than this towards its western and eastern limits, while it is much greater near the meridian. Thus, during the nine years be-

tween 1814 and 1823, the progress westward was only 11′ 22″ or 1′ 1.6″ annually; while from 1657 to 1672 the variation amounted to 2° 30′ or 10′ annually. Between 1672 and 1682 it amounted to 2° or 12′ annually. Between 1692 and 1722, the average annual increase was 16′ 40″. This was the maximum. After the year 1722 the rate diminished very rapidly. It seems to have reached half way or 12° of western declination about the year 1714, that is, in 57 years. To complete the other half, a hundred years were required. These circumstances render it impracticable to calculate the length of the period of the variation from any data in our possession. Corresponding changes have been observed in many other places. Those at Cambridge, Mass., will be found at the end of the book. The same Table will show that similar variations were early observed in the value of the *inclination* at London and Cambridge.

191. We find the following curious notices of the *daily* changes in the elements. At Paris, according to M. de Cassini, the maximum of diurnal declination occurs between noon and three o'clock in the afternoon, when the needle is stationary; it then approaches toward the terrestrial meridian till about eight o'clock in the evening; from which time it ceases to change its position, remaining stationary during the night. The next day, at about eight o'clock in the morning, it recommences its motion from the meridian. If this second departure exceed the first, we infer that the declination is increasing from day to day; in the contrary case, it is supposed to be diminishing. The greatest diurnal variations usually take place during the months of April, May, June, and July; that is, between the vernal and autumnal equinox. At Paris, they vary from 13′ to 16′. The smallest are from 8′ to 10′; and they take place during the remainder of the year. Now if we compare similar situations of the needle on different days, and at corresponding hours, in order to determine its general course, we shall find that from the vernal equinox to the summer solstice, the north pole of the needle inclines towards the east, and that it tends westward the rest of the year, that is, from the summer solstice to the vernal equinox. M. de Cassini deduced these periods from eight years' observations, made at the observatory in Paris.

The mean diurnal variation at London, as deduced by Mr. Gilpin

from 12 years observations, namely, from 1793 to 1805, is as follows; March 8′.5, June 11′.2, July 10′.6, September 8′.7, December 3′.7. The amount, however, of this change must evidently depend upon the strength of magnetism in the needle, the freedom of its motions, &c. It may accordingly be increased almost indefinitely by diminishing the directive force, and removing, as far as possible, all impediments to motion. Thus by reducing the directive force in the ratio of 1 to 0,034, by means of two bar magnets, placed in the line of the dip, Mr. Christie found a diurnal change in the direction of the horizontal needle, amounting to more than 10°.

The dipping needle is likewise subject to daily variations, especially when its directive power is diminished. Mr. Barlow observed in general, that a motion commenced soon after the instrument was adjusted in the morning; but it was not of that gradual progressive kind which indicated a uniformly increasing or decreasing power, as in the horizontal needle. It passed, for instance, suddenly from one half or quarter degree to another, more or less, and which sometimes in the course of the day would give a difference in the dip to the amount of a degree and a half, or even more; but he seldom saw in it a tendency to return; although when he vibrated it toward night, it commonly took up its morning position. He made these observations with the needle in various directions, viz. with the face of the instrument to the east, west, north, south, &c.; but in every case he obtained the same sort of daily motion. The question, therefore, respecting the law of variation of this instrument, still remains to be submitted to fixed principles, although there can no longer be any doubt, that it is subject to a daily change. An ingenious Norwegian observer, M. Hansteen, has found that the intensity, like the declination and inclination, has its variations both annual and diurnal. It generally decreases from morning until about eleven o'clock, and then increases until four o'clock in the afternoon in winter, and six or eight in summer. Its minimum takes place in January, and its maximum in July. These early results on the variations of the elements have been substantially confirmed at the magnetic observatories which are in operation in various parts of the world.*

* See Memoirs of the American Academy, II. vol. New Series.

192. It appears, moreover, by numerous observations, that the magnetic needle is subject to sudden and irregular variations at the time of the luminous meteor, called the *aurora borealis*. These variations are frequently of but short continuance; that is, after the needle has been thrown into rapid agitations, during the appearance of the meteor, it resumes its ordinary position, and recovers its wonted motions; but it sometimes happens, that the deflection is permanent. It has also been remarked, that there are instances in which the needle is apparently under the influence of the meteor, when no meteor is to be seen at the place where the phenomenon occurs. But in such cases we always find, that the meteor has presented itself with more or less distinctness, either at the same moment or a few hours before or after, in some countries farther to the north or south; so that these unusual agitations of the needle may be considered as a proof of the existence of the meteor, and may perhaps be regarded as the precursor of it.

193. The aurora borealis appears in the night at irregular intervals, extending itself along the northern part of the heavens, now as an indefinite faint light, rising a little above the horizon and resembling the twilight; now as phosphoric corruscations, suddenly traversing and illuminating the whole atmosphere. These luminous appearances were for a long time the only circumstance that engaged the attention; but in 1740, two Swedish observers, Celsius and Hiorter, discovered other and entirely new phenomena in this meteor, which, being intimately connected with its nature, very much extended the views which had been previously entertained upon this subject. They observed, that during the appearance of the aurora borealis, magnetic needles, freely suspended, almost always undergo very irregular agitations, which needles not magnetic, those of copper, for instance, do not exhibit. If we compare observations of this kind made at places very distant from each other, as at Upsal and London, for instance, we find that the motions are the same. It appears, also, that their violence depends on the brightness and extent of the aurora borealis. A low and faint glimmering, towards the northern horizon ordinarily produces only a very slight, and perhaps insensible, disturbance of the magnetic needle. Moreover, the motion is very slight in the case of an elevated meteor when the principal focus is situated in the plane of the

needle's direction, usually called the plane of the magnetic meridian. We remark further, that when the phosphoric jets are numerous, the atmosphere at the same time being calm, or only agitated by a steady breeze, we almost always observe that the substance of the meteor is disposed in one or several concentric arcs, resembling those of the rainbow, now white, and now tinged with the brightest colors. But we almost always find, that the common centre of these arcs and their summits are situated in the magnetic meridian of the place where they are observed, so that they are all similarly situated with respect to this plane; and this coincidence with the meridian, which still exists, has been remarked ever since any accurate observations were made, although during this time there have been very considerable variations in the direction of the magnetic meridians in Europe; so that the mean direction of the meteor in the horizon of each place, has also undergone an equal change. Furthermore, it sometimes happens, that the phosphoric fires, breaking forth from all parts of the horizon, from the east, the west, and the north, ascend, or seem to ascend, vertically over the head of the observer, even to his zenith, and having passed this point, they form by their union a brilliant crown, whose centre is situated some degrees lower, near the south east, at least in all places where this remarkable modification of the phenomenon has been observed. But if we determine the apparent position of this crown, either by the aid of astronomical instruments, or by observing what stars are comprehended within it at the time of its formation, we shall find that its centre, in every place where it has been observed, is always situated exactly in the direction of that point in the heavens, to which the magnetic needle is directed, when suspended by its centre of gravity, in such a manner as to admit of its taking its position freely, in obedience to the resultant of the magnetic forces exerted upon it by the terrestrial globe. Biot had an opportunity of verifying most of the particulars here mentioned in the case of a very large aurora borealis, which was visible on the 27th of August, 1817, during his visit to the Shetland Islands.

He first saw in the northeastern parts of the horizon several slender, jets of light which, having attained a little elevation, continued to shine for some time and then vanished; but in about an hour and a half afterwards they re-appeared in the same region of the heavens,

and were now much stronger, more brilliant, and more extended. Very soon a regular arc resembling a rainbow began to present itself just above the horizon. It was at first incomplete, but gradually increased; and after some moments, Biot saw the other part approaching from the west, and upon being formed, it ascended instantaneously, accompanied by a multitude of jets of light which rushed towards it from all parts of the northern horizon; then the summit of the curvature rose almost to the zenith. This arc was at first wavering and unsettled, as if its component parts had not taken a stable position; but very soon the agitation entirely ceased, and it remained in undisturbed beauty for more than an hour, having only a progressive motion, and that almost insensible, towards the south-east, whither it seemed to be carried by a gentle north-western breeze that was then blowing. So that Biot had sufficient time to examine it, and to fix its limits and position with the circle, used in his astronomical observations. He found that it comprehended a portion of the horizon amounting to 128° 42′, and that its centre was situated exactly in the direction of the magnetic needle. The whole region of the atmosphere embraced by this arc in the north-western part of the heavens, was incessantly traversed in all directions by luminous jets, whose different forms, motions, colors, and durations, engrossed the imagination no less than the senses. Most frequently, each jet at its first appearance was a mere stream of whitish light; its size and brightness rapidly increased, and it occasionally presented some very singular variations of direction and curvature. When completely developed, it contracted into a slender rectilineal thread, for the most part exceedingly brilliant, and tinged with a very deep red color. After this it grew fainter and fainter till it finally vanished, often at the very place where it first appeared. The long continuance of many jets in the same apparent place, considered in connexion with the infinity of shades assumed by them, seems to prove, that the light is not reflected, but direct, and that it is actually developed in the place where it is first seen; besides, Biot was not able to discover in it the least trace of those physical properties which characterize reflected light; and which are designated by the term *polarization*. All these fires, and even the arc which comprehends them, occupy a region more elevated than the clouds, since the clouds themselves intercept them;

and the edges of these clouds were actually or seemed to be tinged with light. The moon, which had then reached a considerable elevation above the horizon, shed her lustre also on this imposing scene, and the tranquillity of her silver light formed a most agreeable contrast with those vivid corruscations with which the atmosphere was inundated.

194. Having now given a view of the principal circumstances attending this phenomenon, we propose to deduce from them the conditions of its existence; and the first thing to be determined is, whether it exists in our atmosphere or beyond it. There is a simple method of settling this question. If it be beyond the atmosphere, it must be independent of the diurnal rotation of the earth; and therefore its jets of fire, its arcs, its luminous crowns ought to follow the general course of the stars from east to west, and to seem like them to turn about the celestial poles. On the contrary, if the meteor belongs to our atmosphere it should partake of the common motion which the rotation of our globe communicates to all terrestrial bodies, and even to the clouds; it should then appear to be immovable with respect to these bodies, or at least to undergo only accidental disturbances like the clouds themselves. All observations unite in establishing the latter supposition; and the length of time during which the meteor, observed by Biot at the Shetland Islands, continued, would, if necessary, afford a fresh confirmation.

We may then consider it as an established fact, that the phenomenon of the aurora borealis takes place in our atmosphere. But, as is well known, elevated objects when seen at a distance through the atmosphere, are apt to produce many optical illusions. For example, all the stars seem to us attached to the concave part of the same spherical surface or dome; although their distances are infinitely various. The vast trains of luminous vapor which form the tails of comets, seem also to apply themselves to this dome, although in reality they stretch into space in rectilineal directions. By another illusion, when the sun is partially concealed behind a mass of clouds, and emits rays of light through the openings of these clouds, the rays, although actually parallel, appear to converge towards the point of the heavens where the sun is. These general laws of perspective must affect, in like manner, the appearance of the luminous jets emitted by the meteor in question, and must be

taken into consideration in our attempts to explain them. But from whatever situation these jets are observed, they always seem to describe arcs of great circles on the celestial dome, and to converge towards that part of the heavens to which the needle points when perfectly free. Whence we conclude, that they are in reality cylindrical, and parallel to the direction of the needle. But each jet presents, moreover, great varieties of size and lustre, from which we are led to believe that they are, in fact, composed of a great number of shorter cylinders independent of each other, and in part piled one above another. As these indications are noticed throughout the whole region of space where the meteor is visible, we may conclude, with geometrical rigor, that it consists of a forest of luminous columns, all parallel to the resultant of the magnetic forces, and of course for short distances parallel to each other, and suspended at nearly equal heights on different sides of the horizon. These columns being situated at different distances from the observer, must, by the perspective effect, appear to be raised to different heights. They must also mutually cover each other, and appear to project one over the other, especially when, being seen near the horizon, the visual rays proceeding from them are nearly perpendicular to their length; but after attaining such an elevation that their intermediate spaces may be seen, they must appear to separate; if then a certain number of them be simultaneously transported over the head of the observer, in such a manner as to pass by the point of the heavens to which the magnetic needle, parallel to them directs itself, the projection of all these columns on the celestial dome, will form about this point a luminous crown the divergent rays of which will seem to descend on all sides toward the horizon, till they arrive at the apparent height at which the meteoric columns will have descended by the effect of the progressive motion.

This constitution of the meteor, which has been deduced from optical considerations, is rendered probable by many curious facts, which different observers have had occasion to notice, and which have a relation to the positions which these different parts of the meteor happened accidentally to have with respect to them.

For example, when the meteoric colonnade, already illuminated, is situated entirely in the horizon exactly north of the observer, if it happens to be transported in a southerly direction, and in conse-

quence to approach the observer, without any disappearance, or change of arrangement, of the columns composing it, we ought to expect the same optical effect which is presented by the trees of a forest when we approach them; that is, the columns situated eastward will separate toward the east, and the columns situated westward of the plane of the magnetic meridian, will appear to separate toward the west, while those which are in this meridian will appear to be stationary, or at least only to ascend directly towards the zenith. This appearance was attentively observed by F. C. Mayer, at Petersburg, in a large aurora borealis, which was seen on the 16th of Sept. 1726. I will quote his very language, observing that by the word "trabs," he designates a vertical jet, or one of our luminous columns. He first describes the formation of an arc, whose summit was not directed exactly to the north, but which had a very considerable declination to the west. He then adds, "Motus trabium mirus erat; quæ enim in occidentali arcûs parte extabant, versùs occidentem ferebantur; ad orientem ferebantur, quæ in orientali arcûs parte sitæ erant; boreales autem trabes stabant immobiles. Ex hoc phænomeno intellexi lucem moveri ex nord-west versùs verticem meum, id quod sequentibus phænomenis confirmatum est." It will be seen that Mayer has deduced precisely the consequences which are required by the rules of perspective.

195. Another case which may sometimes present itself, although very rarely, occurs when the illumination of the meteoric colonnade, seemingly accidental, appears for some time to take place only over a certain number of the columns which compose it. Then if these columns are placed at sufficient distances from each other, we may have an opportunity of examining them singly. This opportunity was afforded by the remarkable aurora borealis of 1716, an account of which may be fouud in the memoir of Dr. Halley, (Phil. Trans. 347, p. 411, 415.) Small columns of equal lengths and parallel to each other were distinctly seen separate in a portion of the heavens surrounded by two luminous and almost horizontal belts. An account of a like phenomenon may also be found in another memoir of Dr. Halley, (Phil. Trans. No. 363, p. 1099, for the year 1719.) He there relates, that from time to time, there appeared in the air at a great height collections of columns, or co-ordinate luminous beams, resembling the pipes of an organ, which presented them-

selves to view as suddenly as if a curtain had been drawn from before them. Indeed, if any one will undertake to read the numerous accounts of this meteor which have been furnished by those who have visited the northern regions, he will find a mass of facts which perfectly answer to the constitution of the meteor as deduced by us from the laws of perspective, and he will not meet with any thing opposed to our conclusions. A full statement of these geometrical deductions has been given by Dalton, probably without being aware that they had been already obtained by Cotes, in 1716, the person of whom Newton said, that "if he had lived, we should have known something;" and that they had since been adopted by Cavendish, the most severe and cautious of all philosophers. I have made this remark in order to show that they may be regarded as rigorous.

196. After having given a general description of the meteor, one of the most essential circumstances to be determined is its elevation. Attempts have been made without number to ascertain this point, by the aid of the same processes which geometry affords for measuring the distances of inaccessible objects; that is, by observing in different places, at the same time, the position of the same part of the meteor. But the difficulty of obtaining this perfect identity as to time and point of the object, renders the application of the method very uncertain; and accordingly the results obtained by it assign to the meteor uncertain heights, varying, in some cases, from twenty to more than one hundred leagues. Still more uncertainty prevails with respect to the length of the meteoric columns, which some have attempted to measure by like processes. If, in fine, the estimates made under certain favorable circumstances appear worthy of confidence, it may be urged, I think, that they are not general; and that, in certain cases at least, the meteor descends much lower than we should thus be led to suppose. This seems probable from the quick and continual agitation of the phosphoric jets, the simultaneous progressive motions of the arcs, like that which a gentle breeze might be expected to give them, the slow and regular transfer of those fleecy portions of phosphoric matter, which travellers in the northern regions assure us they have often seen floating separately in the atmosphere; a phenomenon which was observed at the Shetland Islands, the 6th of September, 1817. It was a dense cloud which slowly ascended above the horizon from the north-east.

Its sides were the centres of a phosphoric light which seemed at one time to remain behind till it was extinguished, at another, to break forth and illuminate the edges of the cloud. We can give no better idea of this phosphorescent appearance, than by comparing it to the dark clouds of our theatres when illumined by lamps from behind. Yet for some moments Biot observed on its inferior surface a small spot where the light seemed to intervene between it and himself. This cloud, having attained a height of about 45°, remained for some time stationary, and then gently moved to the west, still retaining its phosphorescence; some jets of light also, proceeding from the northern horizon, inclined towards the west, as if a wind in the higher regions of the atmosphere, coming from the south-east, was transporting the meteor to other countries. Similar phenomena presented themselves on the 14th of September. These observations, from which we may infer, that the aurora borealis belongs to the region of the higher clouds, seem to render probable an opinion generally prevalent in all northern countries, which is, that the aurora borealis, when very vivid, is accompanied with a considerable noise, and in some cases with one of great violence. We do not forget how little reliance is to be placed on common opinion under circumstances calculated to inspire terror, or when influenced by the frightful appearance of rapid and unexpected commotions; but the assertions thus made, like all others, possess a degree of credibility; and if it is unphilosophical to believe without proof, it is equally so to reject without examination. Let a person apply himself for thirty years to the study of what are called popular prejudices, and we doubt not his labors would be rewarded by many valuable discoveries. If any one will inquire without bias or prepossession into the reality of the sounds alleged to proceed from the aurora borealis, we are persuaded that he will not hesitate to adopt the common opinion, so striking is the coincidence of testimony on this subject. The distinguished natural philosopher Muschenbroek, who wrote about the middle of the last century, reports, that this fact is generally affirmed by sailors employed in the whale fishery on the coast of Greenland. Gmelin, in his account of Siberia, expresses himself in still more decided language; after speaking of the great splendor of the aurora borealis, as presented in these countries, he adds; "However beautiful this spectacle may be, I think it will

be impossible to contemplate it for the first time, without emotions of terror; so constantly is it accompanied, as I have been informed by several intelligent persons, with noises like those hissings and cracklings produced by very large fireworks. The hunters who go in search of the blue fox to the confines of the Frozen Ocean, are frequently surprised by the unexpected appearance of this meteor; their dogs are frightened by it to such a degree that they cannot be kept from stopping and lying on the earth until the noise has ceased." There is a phrase belonging to the language of this country, used solely to express the terror which this phenomenon occasions. Gmelin adds, that there was a unanimous voice in support of what is here stated. I can affirm, moreover, that among the inhabitants of the Shetland Islands, the testimony is no less full and complete, although they do not speak of so loud a noise; a difference to be attributed undoubtedly to the less northern situation of these islands. M. Edmonston, who, like Biot, was unacquainted with the passage just quoted from the work of Gmelin, described to him the noise occasioned by the aurora borealis in very similar terms, giving him to understand that he had very frequently heard it himself; he thought it most like the noise proceeding from a large fire. Biot did not have an opportunity of observing it during the appearance of the meteor when he was at Unst, as the sea then roared with great violence on the side of the island where he was. In fine, the inhabitants spoke only of having heard the noise of the meteor, when the phosphoric jets are very numerous, and when they cross and intermingle with the greatest activity. For the truth of what is here alleged we may appeal with confidence to the whole population of the Shetland Islands; hardly a person is to be found who will deny having heard this noise; we do not however depend on assertion merely; it is described in the same manner by different persons, without their once imagining that there can be any doubt about it. The phenomenon seems to be much more brilliant a few degrees nearer the pole. M. Edmonston, in an account of the appearance of a large aurora borealis which he observed at Unst on the 1st of November, 1818, has afforded us a striking example of this difference. "I am now in company," says he, "with two credible persons who on a voyage from London to the Shetland Islands, were driven by winds to the latitude of 63½°, near the northernmost ex-

tremity of the island. While they were in this latitude an aurora borealis appeared; the noise with which it was accompanied was such that the sailors were afraid to remain on deck; and it sent forth so strong a light, that we were able to observe the compass by it." It seems probable after this mass of testimony, that the meteor sometimes descends so low as to allow us to hear the noise proceeding from it. It has even been affirmed by Bergmann, that persons travelling over the Norwegian Alps have been enveloped in it, and have perceived a strong smell of sulphur, supposed to proceed from it.

197. Having thus collected the several particulars belonging to the aurora borealis, in doing which, I have endeavored to exclude every thing of a hypothetical nature, we may consider this meteor as consisting of real clouds, proceeding usually from the north, and composed of some very light substances, or at least of some substance so finely pulverized as to be capable of floating a long time in the atmosphere, endued with the property of occasionally becoming luminous; and especially (which is very important) sensible to terrestrial magnetism, and spontaneously arranging themselves in columns which turn towards the earth, as real magnetic needles would do. But of all terrestrial substances only the metals, so far as we know, are in any considerable degree susceptible of magnetism. It is then probable, that the columns of the meteor are at least in a great measure composed of metallic particles reduced to powder of extreme fineness. But this conclusion leads also to another; we know that all known metals are excellent conductors of electricity. Now the different strata of which the atmosphere is composed are usually charged with very unequal quantities of electricity; for if, when the atmosphere is most serene, we raise a paper kite with a metallic string, we may observe at the end of the string signs of electricity, ordinarily of the vitreous kind; and if, on the other hand, having ascended in a balloon, we let fall below the car a wire whose inferior extremity shall reach the lower strata of the atmosphere, we shall find, as has been observed by M. Guy-Lussac and Biot, that the superior end of the wire gives indications of resinous electricity. Accordingly, if columns consisting in part of metallic substances, are suspended in nearly a vertical position in the atmosphere, like the columns of the aurora borealis when they

float over regions adjacent to the pole, the electricity of the atmospheric strata at the summit and base of the columns will find in them so many conductors more or less perfect; and if this tendency of electricity to diffuse itself uniformly is sufficient to overcome the resistance arising from the imperfect conducting power of the columns, it will flow along these columns, illuminating its path, as is often observed in conductors which are not continuous. When this passage takes place in the higher regions of the atmosphere where the air, on account of its rarity, offers very little resistance, the electricity will flow on silently with all those variations of light which we observe in exhausted tubes. But if it extends itself to the inferior strata, it must necessarily occasion such hissing and crackling noises, as are found to accompany the aurora borealis, when it descends near the surface of the earth. In fine, as the meteor is visible only by means of this accidental circumstance, there is reason to believe that it may exist in the air and exert an influence over the magnetic needle without being perceived; it is also very possible that it may be bright in some places and obscure in others; while under certain circumstances the disturbance of the electric equilibrium being sudden and general, the whole meteoric colonnade may be instantaneously illuminated. These phenomena must be less striking as the meteor advances over the more southern countries, not only because it has then extended itself more widely, but especially because the conducting columns, always conforming to the direction of the magnetic needle, will become more and more horizontal, and will have their two extremities in atmospheric strata less distant, and therefore less unequal with respect to the quantities of electricity with which they are charged; a greater humidity also which prevails in the lower latitudes is favorable to a frequent discharge.

All these results, agreeing so exactly with what we have collected from actual observation, it will be seen, depend solely on the idea, that the columns of which the aurora borealis is constituted, are partly, at least, of a metallic nature. This agreement with known phenomena considerably increases the probability of the supposition to which we were previously led by the magnetism of the meteoric columns; the mutual connexion and intimate dependance, thus easily established between phenomena so numerous

and, at first view, so remote, gives an air of reality to the whole, seldom to be met with in physical theories which have not the basis of established fact.

198. But, independently of the luminous jets which may thus be produced by the simple passage of electricity along the metallic columns, a passage which in virtue of a property lately discovered, might of itself be sufficient to magnetize these columns; we can hardly help considering the phenomena in question as proceeding from an actual combustion in the phosphoric clouds, which, detaching themselves in some cases from the burning meteor, as affirmed by many observers, among whom is Biot, transport with them the principle of their phosphorescence, and emit at intervals jets of light resembling rockets, which leave after them a whitish train. We must then regard it as at least a very probable supposition, that the aurora borealis is composed of substances, capable occasionally of inflammation, either of a spontaneous kind, or in consequence of a discharge of electricity from the clouds which contain it; a very powerful mode of combination, of which we have frequent instances in our laboratories.

General Theory of Terrestrial Magnetism.

199. The unwearied zeal with which, in recent times, endeavors have been made to examine the direction and intensity of the magnetic force of the earth, at all parts of its surface, is the more worthy of admiration, as it has been prompted by the pure love of science. Great as is the importance to navigation of the most complete attainable knowledge of the lines of declination, more than this is scarcely required for its purposes. Whilst science delights to render such useful services, her own requisitions have a wider scope, and make it necessary that equal efforts should be devoted to the examination of all the magnetic elements.

It has been customary to represent the results of magnetic observations by three systems of lines, usually termed Isogonic, Isoclinal, and Isodynamic lines. In course of time these lines undergo considerable alterations both in position and figure, so that a drawing of them represents the phenomena correctly only for the epoch

to which it corresponds. Halley's Chart of Declination for 1700 is very different from that of Barlow for 1833; and already Hansteen's Dip Chart for 1780 differs greatly from the present position of the Isoclinal lines. Doubtless, in course of time, similar alterations in the lines of intensity will be manifested; but observations of this nature are altogether too recent to furnish such indications at present.

In all these maps there exist spaces either blank, or in which the lines are but indifferently supported by observation. The inaccessibility of parts of the earth's surface renders perfection in this respect impossible; but a rapid progress towards it may be confidently hoped for.

Viewed from the higher grounds of science even a complete representation of the phenomena after this manner is not itself the final object sought. It is rather analogous to what the astronomer has accomplished, when, for example, he has observed the apparent path of a comet in the heavens. Until the complicated phenomena have been brought in subjection to a common principle, we have only building-stones, not an edifice.

The astronomer, after the comet has disappeared from his view, begins his chief employment, and resting on the laws of gravitation, calculates from the observations the elements of its true path, and is thus enabled to predict its future course. And in like manner the magnetician proposes to himself as the object of his research, as far as the different and in some respects less favorable circumstances permit,— the study of the fundamental causes which produce the phenomena, their magnitude and their mode of operation,—the subjection of the observations, as far as they extend, to those elementary principles,—and the anticipation, with some approximation at least, of their effects, in those regions where observation has not yet penetrated. It is at least well to keep in view this higher object, and to endeavor to prepare the way for it, even though the great imperfection of the data may render its attainment impossible at present.

200. It is not my purpose here to notice the earlier fruitless attempts to explain the enigma of these phenomena by hypotheses having no physical foundation. A physical foundation can only be allowed to such attempts as have considered the earth as a real magnet,

and have employed in the calculation only the demonstrated mode of action of a magnet operati g a distance. Most attempts of this nature hitherto made have this in common ; — that instead of first examining what the conditions, whether simple or complex, of this great magnet must be to satisfy the phenomena, certain determinate and simple conditions were presupposed, and the subject of inquiry has been the accordance or non-accordance of the phenomena with these presupposed conditions. We see here a repetition of what has often occurred in the early history of astronomy and of other sciences.

The simplest hypothesis of this kind is that which supposes a very small magnet in the centre of the earth ; or rather (as it is not likely that any one ever believed in the actual existence of such a magnet) supposes magnetism to be so distributed in the earth, that its collective action at and beyond the surface is equivalent to the action of an imaginary infinitely small magnet ; much as gravitation towards a homogeneous sphere is equivalent to the attraction of a sphere of equal mass condensed in its central point. In the supposed case, the magnetic poles are the two points where the prolonged axis of the little central magnet intersects the earth's surface ; where the magnetic needle is vertical and the intensity is also greatest. In the great circle midway between these two poles called the magnetic equator, the dip is = 0 and the intensity is half as great as at the poles ; between the magnetic equator and either pole, both the dip and the intensity depend on the distance from the said equator (which distance is termed the magnetic latitude) in such manner, that the tangent of the dip is equal to twice the tangent of the magnetic latitude. Lastly, the direction of the horizontal needle must every where coincide with the direction of a great circle drawn through the northern magnetic pole.

There is in nature only a rude approximation to all these necessary consequences of the above hypothesis. In reality the line of no dip is not a great circle, but a line of double flexure ; equal intensities do not correspond to equal dips ; the directions of the horizontal needle are far from all converging to one point ; and so on. A very slight consideration is sufficient therefore to show the inadmissibility of this hypothesis.

One of the above propositions is however still employed as an

approximation in deducing the line of no dip from the observations of dips of small amount made at some little distance from it.

About eighty years ago, Tobias Mayer used a similar hypothesis, but with this modification; that instead of supposing the infinitely small magnet at the centre of the earth, he placed it at about the seventh part of the earth's radius from the centre; at the same time (probably in order to avoid greater complication in the calculations) he retained the wholly arbitrary supposition, of the plane perpendicular to the axis of the magnet passing through the centre of the earth. In this manner, on a comparison of the observed variations and dips, at a very small number of places it is true, he found them agree very well with his calculation. A more extended comparison would have shown that this hypothesis did not afford a much better representation than the first-mentioned one, of the whole phenomena of the dip and inclination. No observations of the intensity had been at that time made, at least as far as we know.

Hansteen went a step further, by the endeavor to represent the phenomena on the hypothesis of two infinitely small eccentric magnets of unequal strength. The decisive test of an hypothesis must always be the comparison of its results with those of experiment. Hansteen compared his with observations at forty-eight different places, amongst which however there were only twelve at which the intensity had been determined, and only six complete in the three elements. In these comparisons we find in the dip differences of 13° between calculation and observation.*

If these differences are greater than are admissible in a satisfactory theory, one cannot avoid drawing the conclusion, that the magnetic conditions of the earth are not such as to admit of representation by means of a concentration in either one or two infinitely small magnets. It is not denied that with a greater number of such fictitious magnets, a sufficient agreement might be ultimately attainable; but how far such a mode of solving the problem might be advisable is quite a different question. The calculations are extremely laborious

* In the declination there is even a difference in one instance of 29 degrees; but it is proper to estimate the error of the calculation, not by the number of degrees of declination, but by the true angular difference between the calculated and observed directions, which in the case in question is 11½ degrees.

even with two magnets; with an increased number they would probably present insuperable difficulties. This mode of proceeding reminds one of the attempts to explain the planetary motions by continued accumulation of epicycles.

Biot first approached the subject in a more general manner. He proceeded to calculate the action at the surface of the earth of a magnet, in which the distance of the poles was left indeterminate: and afterwards, by a comparison of theory with observation, he calculated the distance which gave the best correspondence. He found that the observed elements could be nearly represented in numbers, by supposing at the earth's centre two magnetic centres or poles infinitely near each other. A mathematical relation was thus established between the magnetic latitude and longitude of any place on the surface of the earth and the inclination of the needle. The numerous observations of Humboldt in remote parts of the globe afford ample scope for comparisons. Krafft afterwards took up the formulæ of Biot, and found for the relation in question this simple expression, viz.; *the tangent of the magnetic dip is double the tangent of the magnetic latitude.* This law, which was published in 1809, holds good at the present day in a large number of cases. Biot, upon attempting to apply the law of the tangents to some of the islands in the South Seas, such as Otaheite, where Cook had frequently observed, found the inclinations much too great, while they were too small for places situated in the same longitude in North America. He attributed these variations to the inflexion of the magnetic equator towards the south pole. For the same reason, the formula is not applicable to the observations that have been made in India. Biot proposed, therefore, a modification of his theory which consists in supposing in these regions a second eccentric magnet, whose position and relative power may be so adjusted, as to satisfy the known observations. But in performing the calculation, he found that it is only necessary to give to this magnet a very feeble force, in orde to explain all those anomalies which occur on this side of the globe, and to reconcile the very small inclinations observed in the Archipelagos of the South Sea, with the large ones observed in the northern parts of the continent of America. By distributing in this manner other secondary centres in those parts of the globe where the irregularities of the decli-

nation seem to be most striking, he thought it would be possible to give an accurate representation of these, as well as of the inclinations and intensities; just as in the solar system the principal motion, which is that caused by the attraction of the sun, is modified by the disturbing forces produced by the small masses of the planets. But as it is necessary to know the places of these planets, in order to calculate their influence, so it is necessary that the places of these secondary centres should be indicated by accurate observations before we can calculate their effects; and even then the simplicity of the first hypothesis would be surrendered. In fact, could the secondary centres be dispensed with, the supposition of an infinitely small magnet in the interior of the earth, amounts of course to abandoning the idea of being able to represent the facts of terrestrial magnetism by an ordinary magnet. Whatever be the remote source of the earth's magnetic energy, clearly, it is not reducible to the action of a single common magnet.

201. Poisson has taken up the theory of magnetism and discussed it in all its generality. Although his formulæ are seen to contain the law of the tangents to which we have referred, yet he made no especial application of them to terrestrial magnetism, and therefore they are not of so much interest in this discussion. Within a few years Gauss has undertaken to develope the general theory of terrestrial magnetism, independently of all particular hypotheses as to the distribution of the magnetic fluids in the body of the earth. The force which at each part of the earth imparts a certain direction to a magnetic needle suspended by its centre of gravity, (supposing it free from all extraneous influence, such, for example, as that of another artificial magnet, or the conductor of a galvanic current,) is termed the earth's magnetic force, in so far as the source whence it is derived is to be sought for in the earth itself. It may indeed be doubted, whether the seat of the proximate causes of the regular and irregular changes which are hourly taking place in this force, may not be regarded as external in reference to the earth. We may hope, that from the general attention now directed to these phenomena, much light may shortly be thrown upon their causes. But it should not be forgotten that these changes are comparatively very small, and that there must therefore exist a much more powerful and constantly acting principal force, of which we assume the

seat to be in the earth itself. A consequence which follows from this consideration is, that the facts which are to serve as the foundation on which the study of the principal force must be based, ought properly themselves to be first freed from the effects of the anomalous changes. This can only be done by mean values, drawn from numerous and continued observations; and until we shall possess such purified results, from a great number of stations distributed over the whole surface of the globe, the utmost that can be looked for is an approximation, in which there must still remain differences of the order of these anomalies.

The foundation of these researches is the assumption, that the terrestrial magnetic force is the collective action of all the magnetized particles of the earth's mass. We represent to ourselves magnetization as a separation of the magnetic fluids. Admitting this representation, the mode of action of the fluids (repulsion of similar and attraction of dissimilar particles inversely as the square of the distance) belongs to the number of established physical truths. No alteration in the results would be caused by changing this mode of representation for that of Ampère, whereby, instead of magnetic fluids, magnetism is held to consist in constant galvanic currents in the minutest particles of bodies. Nor would it occasion a difference if the terrestrial magnetism were ascribed to a mixed origin, as proceeding partly from the separation of the magnetic fluids in the earth, and partly from galvanic currents in the same; inasmuch as it is known, that for each galvanic current, may be substituted such a given distribution of the magnetic fluids in a surface bounded by the current, as would exercise in each point of external space precisely the same magnetic action as would be produced by the galvanic current itself.

In developing the subject, Gauss has made use of Laplace's celebrated cöefficients, and by strong powers of analysis combined with accuracy of numerical calculation, has succeeded in bringing his equations into a form which admits of ready comparison with observation. He has already satisfied himself of the general accuracy of his theory by such comparisons as the existing state of observations rendered possible. The scientific men, in various and remote quarters of the globe, are now busy in collecting new and more accurate data, and when the present magnetic crusade is

finished, we may expect in the complex subject of the earth's magnetism a completeness of theory and a nicety of observation that shall rival the attainments of the astronomer.

202. A part of the theory on which there may exist a doubt is, the supposition that the agents of the terrestrial magnetic force are situated exclusively in the interior of the earth. If we seek for their immediate causes, partly or wholly, without the earth, and confine ourselves to known scientific grounds, we can only think of galvanic currents. But the atmosphere is no conductor of such currents, neither is vacant space; thus, in seeking in the upper regions for a vehicle of galvanic currents we go beyond our knowledge. But our ignorance gives us no right absolutely to deny the possibility of such currents; we are forbidden to do so by the enigmatical phenomena of the Aurora Borealis, in which there is every appearance that electricity in motion performs a principal part. It will therefore still be interesting to examine what form magnetic action arising from such currents would assume on the surface of the earth. Gauss carefully follows up this suggestion, and exposes the fallacy of the hypothesis which looks for the chief source of terrestrial magnetism in spaces external to the earth.

Practical Instructions as to the Method of observing the Elements of Terrestrial Magnetism.

203. Magnetic observations being at this time especially one of the most important objects that can engage the attention of scientific travellers, I have thought it would be useful to subjoin a few practical instructions respecting the processes to be employed in making such observations with accuracy. To begin with the most simple case, I will suppose that the observations are to be made on land; I will then describe the additional precautions necessary on board of vessels, liable always to be more or less agitated, and which may themselves exert a considerable disturbing force on the needle in consequence of the iron used in and about them. The first element to be determined is the declination, that is, the angle comprehended between the magnetic needle and the plane of the astronomical meridian. The instruments destined for this purpose are

called *declination* or *azimuth compasses*. Among the different forms which have been used, the preference was long given to that invented by M. Cassini, to which an ingenious artist M. Gambey added an improvement, that gave it a decided superiority over all others. It is represented in figure 123.

This compass is composed principally of a long magnetic needle of a rectangular form, suspended edgewise in a horizontal position by an assemblage of flat silk threads without any sensible torsion, and surrounded by a horizontal graduated circle, *EOV*, which enables us to measure the extent of its motions. The point of suspension is at *C* in a cross bar of copper, supported by two columns of the same metal; and these columns are inserted at their bases into a plate also of copper, which rests on a pivot in the centre of a circle; so that the whole apparatus admits of being turned about this centre, like a common surveying instrument. A branch of copper *B*, attached to one of the columns, carries a vernier *V* over the graduated circle *EO*, that is employed in measuring this motion. Moreover to guard the apparatus from the agitation of the air, it is completely enclosed in a glazed box of wood or copper, which rests upon the same metallic supports. Having assured ourselves of the perfect mobility of the needle, it only remains to determine the point of the horizon to which it directs itself. For this purpose, by means of the transverse axis *AA'*, we attach to the summit of the two columns a telescope *LL*, which is movable in a vertical plane, the axis *AA'* being horizontal. To give the axis this position, we first make the graduated circle *EOV* itself perfectly horizontal by means of the adjusting screws v, v', v'', and spirit levels placed upon its surface. We then suspend a spirit level to the axis *AA'*, by means of two hooks; and if it is not already horizontal, we make it so by the aid of a little apparatus of movable pieces attached to the columns and admitting of a vertical as well as a horizontal motion in one of the ends *A* of the axis. Now the telescope *LL* contains in its interior two very fine hairs or wires, situated in the focus of the eye-glass, whose point of intersection serves to fix the precise direction of the visual ray. But these wires are so placed by the instrument-maker, that the visual ray which passes through their point of intersection is exactly perpendicular to the axis *AA'*, and passes through its middle point. Besides, the telescope has not a

simple spherical lens for an object-glass; but two such lenses placed one over the other, very unequal both as to curvature and dimensions; one, occupying the larger part of the tube, throws a distinct image of distant objects on the wires; the other, which is much smaller, is so formed that when combined with the larger, it throws on the same wires the image of very near objects. Moreover, the direction of the visual ray, which passes through the intersection of the wires, is regulated by the two lenses in the same manner. Accordingly, if we would see only very near objects with the telescope, we have merely to cover all that portion of the larger glass for which we have no use, by attaching to the end of the instrument an opaque cover having a circular opening at the centre, as represented in figure 124; and, on the contrary, if we would look at distant objects we substitute another cover, opaque at the centre and open toward the circumference, as shown in figure 125. This being well understood, we can determine the direction of the magnetic needle in the following manner; we first turn the box until the needle attains a free and unobstructed position; and when it is stationary we direct the microscopic part of the tube *LL* successively towards the two ends of the needle, where are attached cross wires which serve for signals. It seldom happens, that the point of intersection of the wires is, on the first trial, in a line with the intersection of the wires of the telescope; but as we can move the axis of the telescope in a horizontal direction, and also turn it by means of the arm *B* attached to the columns, it is always possible to bring the intersection of the wires of the telescope to coincide with the image of the signal carried by the needle; and it is moreover necessary, that this coincidence should be effected at each end of the needle. When this condition is fulfilled, the optic axis of the telescope, that is, the visual ray which passes through the intersection of the wires, will evidently be in the same vertical plane with the line drawn through the two signals, affixed to the extremities of the needle. This plane will then be that of the magnetic meridian, if the line above-mentioned coincide with the magnetic axis of the needle. Let us suppose for the present that this is the case. We have, therefore only to take from the end of the telescope the cover by which it was fitted for near objects, and to substitute instead of it that which answers to the small lens, in order that we may dis-

tinguish distant objects; then, directing the telescope to some point near the horizon, which is directly in the line of intersection of the interior wires, we shall have the position of the magnetic meridian; and thus we may discover the declination of the needle by measuring, at our leisure, the angle comprehended between this line and the geographical meridian of the place. This problem belongs to astronomy. But it is not by any means certain that the line drawn through the two signal points of the needle is its magnetic axis; we must, therefore, know how to determine this axis, which is done in the following manner. Let $ABCD$ represent a magnetic needle, Fig. 96. suspended horizontally by a number of untwisted silk fibres, either immediately or by means of a small paper or copper dish. When this needle is in equilibrium, its magnetic axis GG' will be directed in the magnetic meridian of the place. This, however, is not sufficient for determining it, since its position in the needle is only ideal; but, from the nature of parallel forces, we know that, whatever position be given to the needle, this axis must remain fixed, and preserve invariably the same situation relatively to the surface by which it is bounded. Having now observed to what terrestrial object one of the sides AB is directed when it is in equilibrium, we then turn it upside down, and suspend it anew horizontally by the same kind of suspension as in the first experiment. The magnetic axis GG' will again place itself in the direction of the magnetic meridian; but the sides of the needle having turned circularly round this axis, will not again place themselves in the same direction as before; and, what is a point of great importance, they will deviate from the magnetic meridian as much as they did before, but in an opposite direction. This is shown in the figure where the dotted line $A'B'C'D'$ represents the position of the surfaces after their reversion. Having observed the direction of one of the sides AB of the needle in its first position, if we do the same for the second, the true direction of the magnetic meridian will be exactly midway between them. We may thus determine and note it on the surface of the needle, or mark the point of space to which it corresponds when prolonged. This process is easily followed with the instrument represented in figure 123, where the needle is enclosed in a copper cylinder. In order to reverse it, therefore, it is sufficient to turn it upside down by shifting the cylinder; after which we ob-

serve anew the direction. If we obtain the same point in the horizon as before, we have no correction to make; but if the second direction differs from the first, as is most generally the case, we must refer them both to the geographical meridian, and take the mean of the angles thus observed. This will be the true declination.

204. This reference to the meridian can be very accurately made with the same instrument. For, when we have found the point of the horizon, to which the axis of the telescope is directed, we observe the number of degrees, &c., in the horizontal circular division to which the vernier of the arm *B* corresponds. This being done, without touching this circle again or deranging it at all, give free motion to the box and columns, without now regarding the needle, and turn the arm *B*, until the telescope is directed towards some known star then situated near the horizon. Observe, by means of a good chronometer, the precise moment when this star is directly behind the point of intersection of the wires, and we can hence deduce by calculation the angle comprehended between the geographical meridian and the vertical plane in which the star is situated at this instant. But having noted the point of the graduated circle to which the vernier of the arm *B* corresponds, we shall know the angle which this same plane makes with the magnetic meridian, in which the telescope was at first directed; we shall thus obtain the angle formed by this meridian and the geographic meridian.

As we have seen that, in the same place, the magnetic needle undergoes slight periodical variations, it is necessary in order to obtain an accurate estimate of the declination, to repeat these observations at such days and hours that these variations may be eliminated from the mean result; we must also be on our guard against those circumstances under which the needle, employed for the diurnal variations, has indicated the existence of disturbing causes. In general, if we aim at great accuracy, it is indispensably necessary to note the day and hour of the observations. We may use the same instrument to measure the diurnal variations themselves, which it is an object of no less interest to observe in places remote from each other.

205. The method just explained for finding the absolute declination, is essentially the same with that used for observing the declination of the magnetic needle at sea; but in order to render it fully

applicable to this purpose, certain modifications are necessary. We must, in the first place, dispense with the telescope, which it would be almost impossible to use on account of the motion of the vessel, and substitute for it simple threads, stretched vertically over plates of copper adapted to the circumference of a box which is capable of turning freely in the interior part of the apparatus. The plates have slits cut in them against the threads, and are termed sights. They are so placed that the two threads, determining the direction of the visual ray, fall at the two extremities of a diameter of the circular division. But this division is not in the present case traced on a fixed circle; but on a light disc of pasteboard or horn, which the needle itself carries and directs, its northern point being placed on the division 0°. Besides, as it is not in our power to place the instrument on a fixed plane, we are obliged to suspend it so that it may partake as little as possible of the motion of the vessel, and that it may always tend by its own gravity to the horizontal position necessary for observations. For this purpose we employ *gimbols*, a method of suspension represented in figure 126. In the first place, the instrument is attached to the axis *a a*, which turns freely on two opposite points of the circle of copper; and this circle in its turn is, in like manner, suspended to another axis *b b* perpendicular to the former; so that if we incline the exterior supports of the instrument in any manner whatever, provided we do not exceed certain limits, the box, suspended on the first axis *a a*, will remain upright in all positions of the vessel, and indeed its own weight will always restore it more or less readily to this position; so that there is the least possible disturbance of the needle, especially when it is so adjusted that its centre falls at the point of intersection of the two axes of suspension. When the azimuth of an object is to be taken with this instrument, we turn the box containing the needle until the threads of the sights are directed towards it; and as the needle, on account of the directive force, does not partake of this motion, the diameter of the circular division, answering to the threads, indicates the angle comprehended between the direction of the object and that of the needle. In order to facilitate this operation, the artist traces on the interior of the box two fixed lines on a level with the graduated disc which the needle carries. We may immediately determine the numbers of the division to which these marks

correspond, when the diameter answering to the threads coincides with the direction of the needle; and then the numbers against which it falls when the box is turned a certain angle will measure the amount of the deviation. When the observation is made at sea, two observers are necessary; one directs the sights, while the other determines upon the box the mean place of the needle, which is continually agitated by the motion of the vessel.

206. Captain Kater made a very ingenious improvement which adds greatly to the accuracy of such observations, while at the same time it facilitates them. It consists in placing the observer so that he can see, at the same time and with the same eye, a very fine thread which projects itself on the distant object whose bearing is to be taken, and also the point of the circular division which answers to the direction of the visual ray coming from this object. We effect this double purpose, by causing the image of the distant object to reach the eye, by direct vision, and that of the circular division, by reflection from an inclined mirror.

After this suggestion, in order to have a perfectly clear idea of the process, we need only a description of the instrument. It is represented in figure 127. It consists of a copper box whose diameter is about two and a half inches, and whose circular bottom supports a steel pivot with a fine point, on which is placed the centre of the magnetic needle, the cap used for this purpose being of agate, that the motion may be more free. This needle, like those of the mariner's compass, carries a light circle of pasteboard or horn, with a graduated circumference, zero coinciding with the north point. The whole is covered with very transparent glass which preserves the needle from the agitations of the air. The apparatus substituted for sights is composed of two pieces *A* and *B*; the first, *A*, is a plate of copper fixed perpendicularly to the plane of the box, having a slit cut in it, through the middle of which is stretched a very fine thread, that must during the observation remain vertical and perpendicular to the plane of the circular divisions. This condition may be fulfilled by attaching to it a small weight, and levelling the box until it strikes against the fixed point *F*, marked at the foot of the plate. Opposite to this plate of copper is the piece *B*, where the eye is applied. It chiefly consists, 1. of a small hole *T*, through which we are to look at the direction of the thread *F*, and the

object selected for the point of sight. 2. Of a small piece of a hemispherical lens, doubly convex, designated by *C*, which by magnifying enables us to see the degrees of the circular division, the image of which is reflected by a small silver mirror *M*. As the pupil has a sensible diameter, we shall be able to see in these two ways at the same time. Then the vertical thread appears like a slender mark on the reflected image of the divisions, which are diametrically opposite to it; and this superposition determines with no less facility than exactness the direction of the visual ray. For example, the instrument being horizontal, if we turn it until the thread is projected on 180°, the line of vision will exactly coincide with the direction of the needle, and the declination of objects situated in that direction will be nothing. But if we turn the box horizontally through a certain angle, by which means the visual ray is directed towards other objects, the needle which remains constantly directed towards the same point of space, will preserve unchanged the circular division, and the sight thread will be projected on some other point of the divisions, and we may thus measure the angle passed over.

207. The remarkable attention which has been given within the few last years to the subject of Terrestrial Magnetism has led to the invention of several very delicate and ingenious instruments for making observations upon the magnetic elements. Professor Gauss, of Gottingen, has devised a beautiful way of observing the variations of the magnetic meridian. He suspends a very heavy bar of magnetized steel by a number of untwisted fibres of silk six or eight feet in length, and in such a way as to have the least torsion. To one end of this bar is attached, at right angles to its length, a plane mirror, the object of which is to reflect the divisions of a scale which is placed ten or twelve feet in front of it into the field of a telescope which stands at nearly the same distance on the same side of the bar. The division of the scale which is intersected by the middle vertical wire of the telescope determines the position of the needle, and the successive readings of the scale during the twenty-four hours will furnish the daily changes of magnetic declination. If the telescope is attached to a Variation-Transit, the absolute declination may be determined by this instrument. Its great value, however, consists in the simplicity and accuracy with which the daily and

other *changes* are observed. An instrument, similar to the Declination Magnetometer of Gauss, has been employed for some time at the Magnetic Observatory of Cambridge, and is in extensive use in Germany. Professor Lloyd of Dublin, has made some change in the instrument, by placing at one end of the Magnetometer a finely graduated scale, and at the other a lens whose focal length is equal to the length of the bar. In this way the rays of light from the scale, being situated in the focus of the lens, emerge parallel to one another, and are seen through a telescope placed in front of the lens as though they had come from a distant body. This is one of the instruments recommended in the Report of the Committee, appointed a few years ago in England, to suggest means for conducting a complete system of magnetic observations. An instrument of this kind is used at Cambridge and many other of the Magnetic Observatories.

208. We come now to speak of the manner of observing the magnetic inclination. The instrument to be employed, called the Dipping-needle, has been so far described that it is unnecessary to advert particularly to its construction here. I will only remark, that it contains the same apparatus for levelling as the declination needle, and that it is in like manner placed upon some solid support when used on land. But at sea it is suffered to hang freely by a ring attached near its upper surface, which makes a part of the suspension by gimbols. In order to observe the inclination in the two cases, we must first bring to the magnetic meridian the vertical plane which contains the needle; and the angle in question is determined by the vertical circle itself, in the centre of which the needle is suspended. This may be done in three ways. 1. By reducing this plane to the direction of the magnetic meridian previously determined. 2. By first seeking the direction of the azimuth, in which the needle is exactly vertical, and then turning this plane 90°. 3. By turning and preserving the limb in the direction of the azimuth, in which the inclination of the needle is the least possible. Although this last method is less precise than the two others, it still gives results of very considerable accuracy, since for a space of some degrees on each side of the magnetic meridian the inclination is nearly the same as in the plane itself. Indeed, it is the only method that can be employed at sea, because the continual agita-

tion of the vessel does not allow us to establish any fixed relation between two absolute and successive positions of the plane of the limb in space.

The limb of the instrument being placed, by one or the other of these methods, exactly or very nearly in the direction of the magnetic meridian, let us call that face of the needle which is directed towards the east, *E*. When in this position, we must carefully note the point of the division at which the needle becomes stationary when on land; or, which is equally accurate, and admits also of being applied at sea, we notice the extreme limits of the oscillations when these extend only through a small space. We make these observations at each end, and take the mean of the results, by which method we avoid the error arising from the eccentricity of the needle, if it does not happen to be suspended exactly in the centre of the circular divisions. This supposes that the two points of zenith and nadir in the graduation, are exactly in the same vertical. On land we may reduce them to this position by making the instrument horizontal by means of the levels attached to the circular base. At sea this cannot be done, except by taking a mean of ten or twelve observations, in the course of which, on account of the motion of the vessel, the zenith of the divisions will vibrate on each side of the true zenith. Having thus observed the inclination with the face *E* of the needle turned towards the east, we repeat our operations with the same face *E* turned towards the west; taking care to use all the precautions recommended in the first experiment.

This turning of the instrument, as in the case of the declination needle, serves to correct any error arising from the position of the magnetic axis of the needle, which differs but little for the most part from the geometrical axis, but does not always coincide with it. The precaution therefore should never be omitted.

The mean of the four observations thus obtained would be the true inclination, if the needle were suspended exactly by its centre of gravity. But however careful the artist may have been to effect this, he seldom succeeds in doing it with mathematical accuracy. Hence the excess of weight in one arm of the needle must increase or diminish the inclination. But this error may be corrected by another elimination. For this purpose we remove the needle, and reverse its poles by magnetizing them anew with powerful mag-

nets. We then repeat the four observations above described. We shall thus obtain a new value for the inclination, the error of which will be directly opposite to that of the first set of observations, and if the needle is carefully made, by taking the mean between them, we shall obtain the true inclination. This operation of changing the poles should never be dispensed with except from absolute necessity. By an observation is meant in every case eight or sixteen readings of the instrument, so that the final result is made to depend on 64 or 128 single observations. Lloyd has recently published, in the Transactions of the Irish Academy, equations for determining the dip from a needle which is loaded. The best Dipping-needles come provided with two needles. The operation above described is repeated with the second needle, and thus a still more accurate mean value is deduced for the dip.

209. It now remains for us to speak of the intensity of magnetic forces. It may be deduced from the oscillations of a horizontal needle, combined with the observed value of the inclination. Let N be the number of seconds employed by the needle in making a certain number of horizontal oscillations, in a place where the intensity of magnetic force is designated by R, and where the zenith distance of the magnetic axis is Z; if we denote by N', R', Z', corresponding quantities for any other place, we shall have

$$R' = R \frac{N^2 \sin Z}{N'^2 \sin Z'}.$$

This method may be employed especially when we are not in the neighborhood of either magnetic pole; but to render it exact, several precautions are necessary. In the first place, we must endeavor to suspend the needle in such a manner as to avoid entirely the influence of torsion. This may be done by attaching it to a collection of flat untwisted silk threads. The horizontal position of the needle is then effected by simply placing it in a paper dish, the weight of which must be so small as to have no sensible effect. Of all the different forms, the best for this kind of observations is a long thin parallelopiped. Care must be taken to suspend the needle with its broad surface horizontal, and not edgewise, in order to avoid as much as possible the resistance which the air opposes to its oscillations.

210. If among these four quantities, the dip, the total intensity and the horizontal and vertical components, any two be found by observation, the others are easily calculated. Thus we have seen how the total intensity is obtained from the dip and the horizontal force. The manner of deducing the vertical force from the same data is obvious. If means were possessed of observing the horizontal and vertical forces, the dip and total intensity would follow from the geometrical relation which subsists between them. Professor Lloyd's Horizontal and Vertical-Force Magnetometers, by which the changes of these forces are obtained, furnish a way of calculating, if not the absolute dip, at least the *changes* of dip. A single observation on the dip occupying as we have seen a considerable time, the rapid variations of this element must be found in some such indirect way. On account of the uncertainty which attaches to the Force Magnetometers in consequence of the temperature corrections, it is recommended that the dip should be obtained as often as practicable by direct observations on the Dipping-needle. In the great magnetic survey which is now in process, two days in the week are assigned to this purpose.

211. After this description of the instruments used in magnetic observations, we may add that magnetic observatories have been established in various and remote parts of the world, where a system of uniform and strictly simultaneous observations of all the magnetic elements has gone into successful operation. The observations are all made according to Gottingen mean solar time, and in this way form a part of the series first begun by Gauss, and others of the German Magnetic Association. Once in a month, on Term-days, as they are called, provision is made for uninterrupted observations at intervals, originally of two and a half minutes, but now of two minutes; each observation being the mean result of four independent readings of the instrument. On all other days, a mean value of the elements is obtained for every even hour. A very complete series of meteorological observations constitutes a part of the same general plan. Observations of this kind are now made at Cambridge, Philadelphia and Washington. At Philadelphia, the three instruments are provided with mirrors, and the reflected image of the scale is read at a distance. At Cambridge, the scales are attached to the Magnetometers according to the plan of Professor Lloyd, although some-

times a Gauss Declination Magnetometer is observed cotemporaneously with the English Instrument. It is of great importance that the three magnetized bars should be so placed as not to derange the equilibrium of one another.

212. In the preceding remarks, we have considered terrestrial magnetism as the only force exerted on the needles whose motions are to be observed. Indeed, we may reduce all experiments to this simple case by taking care to remove every magnetic substance, and to have about our persons, at the time of observing, no key or other ferruginous instrument. But it is out of our power to do this when at sea, not only on account of the great quantity of iron used in the construction of vessels, but also from the circumstance of the arms, cannon, and iron utensils of every sort which cannot be dispensed with. All these masses united must exert over the compass needle an influence which is combined with that of the terrestrial globe, and must consequently modify its direction and its motions.

In order to analyse the effects produced by this action, we must first remark, that it may be referred to three distinct causes. 1. It may proceed from a permanent magnetic power imparted to ferruginous masses by the processes necessary to prepare them for use; 2. or it may arise from these masses being accidentally thrown into a magnetic state by the influence of terrestrial magnetism ; 3. lastly, it may be referred to a like magnetic state determined by the influence of the compass needle itself on the ferruginous masses by which it is surrounded. These three causes of deviation exist together or apart, conspire or oppose each other.

213. We can easily reduce the effect of the last cause so as to render it wholly insensible, by placing the compass in such a situation, that no considerable mass of iron shall be in its neighborhood; but we cannot proceed in a similar manner with respect to the two other causes. As their energy does not depend on the needle, we cannot discover their limits. Happily the different effects which they are capable of producing will enable us to distinguish them.

Let us begin with an examination of the first kind of action, namely, that which proceeds from a durable magnetic state belonging to ferruginous masses. In whatever manner these masses may be distributed in the vessel, and whatever may be the nature and intensity of free magnetism in each of them, if they are sufficiently

removed from the needle, as the first condition supposes, we may always combine their action into two resultants, one boreal, the other austral, of equal intensities, and whose direction relative to the axis of the vessel will depend on the distribution of magnetism in these masses, and also on their relation to the compass and to each other. This intensity and this relative direction will remain constant, whatever be the direction of the axis of the vessel, whether it turns to the east, the west, the north, or the south. The resultant with which it acts will only turn with it about the vertical, describing the same number of degrees. But it is not so with the directive terrestrial force. This, always acting in the same direction, since it does not depend on the motion of the vessel, will always tend to restore the needle to its proper direction, that is, to the magnetic meridian of the place. The needle will then be attracted at one and the same time by two directive forces of constant intensities, but of which one only has a fixed direction, the other turning continually and at the same rate with the vessel. With the knowledge of what is here stated we shall be able to assign numerically the law of the deviations to which the needle is subjected by these combined forces.

The verification of this law is very easy. We have only to avail ourselves of some moment when the vessel is at anchor in a safe and quiet harbor; then choosing some distant object in the horizon as a signal, we direct the axis of the vessel towards it, and measure the angle formed by this axis with the direction of the magnetic needle. When this is done, we turn the vessel a certain number of degrees, to be measured by reference to some fixed signal, and again measure the angle comprehended between the axis of the vessel and the direction of the needle. We repeat the same observations till we have gone through the whole circuit of the horizon, and the vessel returns to its first position. At the same time an observer is stationed at the same signal, with another compass, carefully compared with the one on board the vessel, to determine the angle which the line of the needle's direction makes with the line drawn from the signal to the vessel. By transferring this angle to the vessel, we have the quantity by which the line of sight actually differs from the magnetic meridian, as determined by the sole action of the terrestrial magnet, whence we can deduce the direction and amount

of the local deviation experienced by the magnetic needle at sea, in each position of the vessel. When we apply to observations of this kind, the formula theoretically deduced from the hypothesis of a constant disturbing force; we find that it answers sufficiently well for places at a moderate distance from the magnetic equator; but the error increases as we proceed to higher magnetic latitudes.

Another striking proof, that the oscillations thus observed are not simply the effect of a constant magnetic action belonging to the ferruginous matter in the vessel, is, that in the same vessel, laden in the same manner, the same needles undergo variations whose amount and laws become more complicated as we ascend to higher latitudes. If the deviations resulted wholly from a magnetic action within the vessel, and constant in all latitudes, the effect would increase indeed as we approach the magnetic terrestrial pole, since, the resultant of the terrestrial forces then approaching to a vertical direction, the horizontal component, derived from it and which is the directive force of the compass needle, would necessarily become more and more feeble; and this is one of the causes which render observations for the declination in high latitudes so uncertain, the slightest foreign magnetic force that acts on the needle being then sufficient to cause great errors. But this diminution of the magnetic power in the horizontal resultant can also be calculated from the observed inclination; and thus we can take account of it. Yet we find it far from being sufficient to account for the changes which take place in the absolute quantity of the deviations, and the manner of their varying according to the different positions of the vessel.

We infer then, that the phenomenon depends, at least in part, on the instantaneous development of magnetism, produced in the ferruginous matter of the vessel by the influence of the terrestrial globe. And from the difficulty attending our inquiries into the manner in which electricity and magnetism are distributed in any body, however simple its form, even though it were only a portion of a cylinder or a cone, it will be seen how complicated the problem must be when the subject of investigation consists of irregular masses, distributed as to the magnetic compass without order or law. It is very evident, that the calculation is wholly out of the question; so that there remains but one method of determining the law of the deviations, and that is, by comparing experimentally the directions

of the needle at sea and on land for different positions of the vessel, as we have explained above. This was done by the English officers in their first expedition to the polar regions. Now we have thus found, that not only the exact amount of the deviations, but even the law by which they are governed, changes in different places; and this indeed ought to be the case according to theory; for, since there is a motion of the vessel about the vertical, it presents the ferruginous masses to the influence of terrestrial magnetism in different directions, and thus occasions magnetic states of different degrees of intensity. It is only on the magnetic equator itself, and for a short distance from it, that the laws of this change are capable of becoming more simple; since the direction of the terrestrial forces being then horizontal, the development of magnetism is of the same intensity, but of a contrary kind in all positions of the vessel, which are 180° distant from each other. Whence it follows, that by taking the half sum of the deviations in each of these two opposite points, the errors will mutually destroy each other, and the mean of the whole will be the true declination; this result agrees with the observations of Captain Flinders, who first proposed and applied the method of correction which consists in inverting the needle.

ELECTRO-DYNAMICS.

Disturbance of the Magnetic Needle by the Electric Current.

214. The direct influence of the discharge of electricity of tension on magnetic needles was studied long ago by Franklin, Cavallo, and others: the power it exerted of destroying, reversing, or communicating polarity was also pointed out. But M. Oersted, of the Academy of Copenhagen, discovered in 1819 a phenomenon altogether remarkable, namely, the action of the voltaic current upon the magnetic needle. This discovery has led to a great number of valuable researches in France and other parts of Europe.

We shall state the principal facts known at the present time upon this new branch of natural philosophy.

The discovery of M. Oersted may be described in a few words.

If we bring near to a magnetic needle a portion of a conducting wire that unites the two extremities of a voltaic apparatus in action, we shall see that this needle is turned from its direction; and it is evidently the current that produces the deflection, since, if we interrupt it, the needle returns immediately to its former position.*

If the power of the voltaic apparatus is enfeebled, the deviation of the needle becomes less.

The common electrometer indicates the intensity of the electric tension. There was wanting an instrument, that should make

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* The needle is also deflected by common electricity, and that which is drawn from a cloud by a lightning rod.—*M. Colladon.*

known the presence of the electric current in a conductor or voltaic apparatus, and which should indicate its direction and energy. Such an instrument we now possess in the magnetic needle.

When the facts discovered by Oersted were made known in France, M. Ampère analyzed them, and showed that they are reduced to the two following.

FIRST FACT. *Directing Action.*

215. Suppose that a voltaic apparatus is placed horizontally and nearly in the direction of the magnetic meridian, and that a portion of the conducting wire is arranged in the same direction; suppose, moreover, that a magnetic needle is placed above or below the conducting wire, it will be deflected in a manner that may be easily determined by the following rule. *Let a person imagine himself placed in the direction of the current with his face toward the needle, in such a way, that the direction of the current shall be from his feet to his head; the austral pole of the needle will always be carried to the left by the action of the electric current.*

It may be ascertained by the same instrument, that the current exists in the voltaic apparatus, and that it takes place from the resinous to the vitreous extremity, that is, in a direction the reverse of that in the conducting wire; a necessary result from the circumstance, that the conducting wire forms, with the voltaic apparatus, what is called a closed circuit.

The electric current tends to put the needle in a position perpendicular to its proper direction; but the action of the earth prevents our obtaining this result; so that the needle takes a position oblique to the conducting wire. If we destroy the influence of the earth, as M. Ampère has done, by fixing a magnetic needle perpendicular to the axis of the dipping needle, the needle, with respect to which the action of the earth is thus neutralized, will place itself so as to make a right angle with the electric current.

M. Ampère was led to the construction of this instrument by the consideration, that, when a magnetic needle can move only in a plane by turning about an axis perpendicular to this plane, it is always brought by the action of the earth into the situation, in which it makes the least possible angle with the direction of the dipping

needle, which it would take if it were free, so that its austral pole makes the nearest possible approach to the austral pole of the dipping needle. It hence follows, that, if we would find the direction of the needle in any plane whatever, we must project the direction of the dipping needle upon this plane. The line of projection would be that in which the needle would take its position. Now it is evident, that, if the plane is perpendicular to the direction of the dipping needle, that of the needle in question making always a right angle with it, and being incapable of approaching to or receding from it, there is no tendency to any one position rather than another. The apparatus under consideration is represented in figure 123. The magnetic needle moves in the plane of a graduated circle. We give to this circle, and consequently to the needle, any position we choose, by means of the hinges *a* and *a'*. The strips of glass *c*, *c'*, support the conducting wire of the voltaic apparatus.

There are two other ways of rendering a magnetic needle *astatic*. That employed by M. Biot, consists in placing the two poles of a very powerful magnet in the magnetic meridian in such a manner that the austral pole shall be to the north, and the boreal pole to the south; and we vary the distance between this and the needle to be rendered astatic, until the action thus exerted, which is always opposite to that of the earth, shall be just equal to this last; and this point is attained when the needle inclines to no one position rather than another. The last method, which is that of M. Ampère, is represented in figure 129. We attach to a vertical copper wire *ABC*, movable upon the point *C*, two similar needles of steel, whose magnetism is of the same intensity, and whose poles are in opposite directions; so that the earth, acting with equal and opposite forces upon the two needles, in all positions which they are capable of taking, may be considered as having no influence upon them thus united. Similar experiments may be made with a dipping-needle, loaded so as to be horizontal. If the current be placed parallel to its length on either side, it will be brought into a position at right angles to the direction of the current by a motion, depending on the direction of the current and the side of the needle at which it runs. The result is the same as if the needle, used in the first experiments, instead of resting on a pivot, were firmly fixed upon an axis. Then if the whole apparatus were turned over so as to make a dipping-

needle, the conductor moving with the needle, the deflection in regard to the current would be the same as before, though the position of the needle in space would be different.

SECOND FACT. *Attractive and Repulsive Action.*

216. *The second fact consists in this, that a conducting wire, and a magnet whose axis makes a right angle with the direction of the wire, attract each other, when the austral pole is to the left of the current which acts upon it;* that is, when the position is such as the conducting wire and magnet tend to take, in virtue of their mutual action; it being well understood, as M. Ampère has remarked, that it is necessary in order that this attraction may take place, that *the straight line, which measures the shortest distance between the wire and the axis of the magnet, should meet this axis between the two poles.* This observation is so much the more important, as it explains why *the attractive action becomes nothing opposite to the pole, and changes to repulsion when the straight line, measuring the shortest distance between the conducting wire and the axis, meets this axis beyond the pole.* On the other hand, *a repulsion takes place when the austral pole is to the right;* that is, when the conducting wire and the magnet are maintained in a position opposite to that which they tend to assume; provided always, that the straight line which measures the shortest distance falls between the two poles; for, when it falls without, attraction takes place. Corresponding effects take place when the conductor is placed at right angles to a dipping-needle.

The action between the conducting wire and the magnet is always reciprocal, in the cases above stated, as may be easily shown by bringing a magnet near to a movable conductor.

Laws respecting the Intensity of Currents.

217. MM. Biot and Savart have sought by experiment the law according to which the action of a current varies with the change of distance. In this inquiry they made to oscillate, for a given time, a very short magnetic needle, presented to the action of a vertical

current, the distance of which was varied, the length of the wire being so great that its extremities might be considered as having no action upon the needle. This disposition represents an indefinite wire. The needle, rendered astatic by the presence of a magnet placed in the magnetic meridian, would arrange itself, after a certain number of oscillations, in a direction perpendicular to that of the current, since the two vertical parts of the wire would exert equal actions upon the needle; hence the resultant of these actions must be in a horizontal plane. Having found by experiment, that the different oscillations for the same position of the current are isochronous, we infer, that the force which urges the needle is necessarily proportional to the angle of deviation from its final direction. It hence results, that the formula for the pendulum is applicable to this case, and that consequently the force of the current is proportional to the square of the number of oscillations made in a given time. Making the calculation according to the results of our experiments, we find *the whole force of the current upon a magnetic element, austral or boreal, is in the inverse ratio of the distance of this element from the current.*

This law relative to the total resultant of the magnetic elements of the needle and of the current being known, it was shown by M. de la Place, as a necessary consequence, that *the action of each element of the current upon the magnetic element is in the inverse ratio of the square of the distance.* But as the law relative to the distance may be modified by the direction of each distance with respect to the general direction of the wire, it remained to show, whether the coefficient really existed, and what was its composition. To ascertain this, MM. Biot and Savart arranged an experiment of which the result showed, that *the action of an element of the current upon a pole of a magnet, or upon an austral or boreal element, varies in proportion to the sine of the angle made by the direction of the current with the line, which joins the pole of the magnet, or the magnetic element, and the middle of the element of the current.* Whence it will be seen, that the law of the action of an element upon the pole of a magnet, obtained by experiment, is the same as that of an element of the current upon the extremities of a helix, deduced by the calculus from the formula which represents the mutual action of two elements of the current.

Electrepeter.

218. To avoid the trouble and difficulty of reversing the direction of the battery current in electro-magnetic experiments, several pieces of apparatus have been contrived, which are called Electrepeters. Let AA' and BB' represent four brass cups screwing into and passing through the bottom board; b, b', two brass pillars also screwing into and passing through the bottom board, having slits filed in their heads, into which two movable brass frames c, c', fit, being connected by the two ivory rods d, d'; four brass studs a, a, a', a', screw into and pass through the bottom board, their upper surfaces being slightly concaved. The cups, studs, pillars, and frames, are connected underneath the bottom board by pieces of copper wire soldered to them, as follows :— Fig. 130.

Cup A, and studs a, a.
Cup A', and studs a', a'.
Pillar b, and cup B.
Pillar b', and cup B'.

Consequently whichever pole of the voltaic battery is in the cup A, the current passes on to the studs a, a, up the frame c, down the pillar b, on to the cup B. If you now reverse the position of the frames so as to bring their points in connexion with the other two studs, then the direction of the same current will be from cup A, to stud a, up frame c', down pillar b', on to the cup B'. It is only necessary to pour mercury into the four cups for the convenience of connecting the Electrepeter with the battery at one end, and the apparatus for the experiment at the other; it being immaterial which end you use.

On account of the inconvenience arising from the use of mercury in this apparatus, an instrument has been constructed which allows the direction of the current to be readily changed without the fluid metal. It consists of an elevated curved ridge, composed of three stout pieces of brass A, P, B, separated by wood at the dark portions on the Figure; A and B communicate by means of a thick wire Fig. 131.

passing under the base of the instrument. Two thick quadrangular bars of brass, *D*, *E*, pass through a circular piece of wood *F*, and terminate in the binding screws *G*, *H*. The bars *D*, *E*, and the piece *F* moving with it as on a centre, are made to press on the ridge *AB* by means of a screw at *F*. Two other binding screws, *L*, *M*, are connected to *A* or *B* and to *P*. If the bars be placed as in the Figure, the copper plate of a battery being connected to *C*, and the zinc to *Z*, the positive current will flow from *L* to *M*, if they be connected by means of a wire or any piece of apparatus. Let the bars be then moved until the end of *E* rests on *B*, *D* will of course be on *P*, and instantly the positive current will move in the opposite direction or from *M* to *L*. When this instrument is used, a drop of oil should be placed on *A*, *P*, *B*, to allow *D*, *E* to glide readily over them.

Multiplier.

219. From a consideration of the above experiments, it is obvious
Fig. 132. that if a conducting wire be bent into the shape of a rectangle, the needle being placed between its two horizontal branches, the action of a current traversing the wire, will be to move the needle in the *same* direction ; for although one branch is above and the other below the needle, yet as the current moves in opposite directions, its effect on the magnet must be the same in each. Upon this principle, M. Schweiger, of Halle, invented an apparatus for the purpose of showing the feeblest electrical currents, which is called the Multiplier. The construction of this instrument depends upon the equal action of all parts of a conducting wire, and upon the circumstance, that a wire, bent round so as to return upon itself once, produces a double effect, and, indeed, that the effect is proportional to the number of circuits made by the wire. According to this principle, the power of the instrument may be augmented indefinitely, and is usefully applied as a method of detecting traces of electricity infinitely too minute to act on the gold-leaf electrometer.

Fig. 133. Figure 133 represents this instrument, in which *AA* is the base, *CC*, *C′C′*, two upright pieces, supporting the frame *BB*, on the outside of which is a groove, that receives the successive coils of the

multiplying wire. *DD* is an upright stem, destined to support the wire from which the magnet is to be suspended ; all these parts are of wood. *E* is a metal rod, which fits close into an opening made in the support *DD* ; to this rod is attached, by a little wax, a fibre of silk *EF*, which carries at its extremity a magnetic needle. The suspension wire passes through a cylinder, which prevents the multiplying wire from touching it.

There is, moreover, near the magnetic needle a graduated circle, *R*, which measures the deviations. The multiplying wire is of copper or silver, and about a hundredth of an inch in diameter. It is covered with silk through its whole extent, which prevents all communication between the different parts of the wire, that lie upon each other in the groove of the frame *BB*. *H*, *J*, represent the two extremities of the wire.

The use of this instrument will be readily understood. In order to multiply the action produced on the needle by the voltaic current, we have only to establish the communication in such a manner, that the multiplying wire shall become a part of the circuit. The directive force of the earth tends always to bring the needle into the magnetic meridian. Accordingly, if we would give to the instrument all the sensibility of which it is susceptible as a galvanometer, we must diminish this force without entirely destroying it; otherwise, the most feeble currents would have the same effect upon the position of the needle as the most powerful. We reduce the directive force of the earth by suspending two needles, with the poles of the one opposed to those of the other, the one being in the circuit of the wires, and the other without. In some cases where we use the instrument simply as a galvanoscope, the needle may be perfectly astatic. The whole apparatus should be covered with glass to prevent any disturbances arising from currents of air. This instrument is of great value at the present time in electro-chemical researches. To show its delicacy, immerse one extremity *H* of the wire in a drop of spring water, and having connected the other extremity *J* to a piece of zinc immerse it in the drop of water, and the needles will be immediately deflected by the weak current thus set in action. It should be remarked, however, that Figure 133 represents rather Lebaillif's extension of Nobili's astatic galvanometer, than the instrument itself which we have just described. The for-

mer adds to the two needles which are acted on by the upper half of the multiplier two others, which are similarly situated in relation to the lower side of the multiplier; so that the compound system consists of four needles, the two within the coil having their poles in the same direction, and opposite to those of the exterior needles. Under this arrangement, the conspiring effects of all the forces is to produce a deflection in the same direction. It is doubtful whether the additional needles is any refinement on the delicacy of the apparatus, since the mass to be moved is increased in the same degree as the moving force, and hence the quantity of motion must remain the same.

Another form of galvanometer has been constructed which possesses some advantages over the one just described. The needle is
Fig. 134. made of watch spring, and bent into a form concentric with the coil *c*. A piece of brass, *a*, equal in length to the breadth of the coil, is inserted between the two poles of the needle where they come together. The coil, instead of being a continuous wire, is made of several strands, the common ends dipping into the same cups *p* and *n*; *b* is a graduated horizontal circle to measure the deviation. The needles rest in an agate cup at *a*, cemented into the coil, and is kept firm by another pivot at *c*, running into a hole in the coil. It is desirable that the bent needle and the coil should come as near together as possible. It will be readily seen that this needle is rendered astatic by its figure.

220. The deflection of a magnetized needle by a voltaic current, has been happily applied by Mr. Wheatstone to the construction of an electro-magnetic telegraph. We have only to suppose the let-
Fig. 135. ters of the alphabet arranged as in Fig. 134. If, then, five magnetized needles be placed at each letter of the fifth line, as in the figure, and surrounded by a wire which connects by both ends with the other point of communication, it is evident that as soon as a current of moving electricity is sent through any of these wires, the enclosed needle will be deflected in one or another direction according to the direction of the current. If only one needle is deflected, the letter is indicated upon which that stands. Thus any of the five letters, *L, M, N, O, P*, may be communicated. For the other letters, two needles must be employed, and the letter to which they point, after being moved, is the one communicated. Thus

if *P* were to be communicated, *L* and *M* would be deflected; if *Y* were to be communicated, *M* and *O* would be turned. When the distance is great, it has been a great object with the inventor to have these motions effected by as small a number of wires as possible.

Reduction of the Electro-Dynamic Action to Tangential Forces.

221. The action exerted by a conducting wire on a magnet is, obviously not a direct attractive or repulsive one; but is rather a tangential force, by which the opposite poles of the magnet tend to rotate round the conducting wire in different directions, and assume a state of equilibrium when the opposing actions of the wire on both poles become equally balanced. Reasoning on this fact, Faraday concluded, that if the action of the current could be confined to one pole only of the needle, perpetual rotation, providing no opposing forces interfered, might be produced. After a series of experiments on this subject, he succeeded perfectly, and thus developed one of the most interesting and extraordinary phenomena in electrical science.

A convenient apparatus for illustrating this rotation of magnets round a conducting wire consists of two or three slender magnets *N*, *S*, and *N'*, *S'*, &c. fixed equidistant from each other, with their Fig. 136. poles in the same position, in the piece of wood *A*, supported by a pointed wire, so as to move readily on its centre. The middle of the piece of wood, *A*, is excavated and contains a few drops of mercury, communicating by means of a curved wire with the external circular trough of mercury *E*. A pointed copper wire, supported by a screw at *C*, dips into the mercury in *A*, and is furnished with a cup containing mercury, so as to be readily connected with a voltaic current through the electrepeter. The cup *C* and the trough *E* are then connected, the former with the copper, the latter with the zinc plate of the battery. So that the positive current descends to *A* and then reaching *E* through the curved wire escapes to *Z*. It thus acts only on the poles *N*, *N'*, &c. of the magnets, which if austral poles, will immediately begin to rotate round the conducting wire *CC*, from left to right, or in a direction like that of the hands

of a watch. By turning the bars of the electrepeter, or otherwise changing the direction of the current, the direction of the rotation will be immediately altered. The same thing occurs, if the position of the poles of the magnet is altered. Let the magnets or currents be arranged as they may, the direction of the rotation always corresponds to the statement of article 215. It may here be remarked, that in this as in all other experiments of this kind where wires dip into mercury, a very perfect contact is required; and this is secured by cleaning the ends of the wires and then amalgamating them by dipping them into a solution of nitrate of mercury. As this, however, makes the ends brittle, a still better way is to cover them over with solder.

The preceding experiment may perhaps be regarded rather as the rotation of a compound magnet about its axis, when the conducting wire is in the interior of the system of magnets, than the revolution of a magnet about a wire. It may be well, therefore, to add other
Fig. 137. cases of undoubted revolution. Let *AB* be the section of a vessel containing mercury. *NS* is a strong cylindrical magnet attached by a thread to a large wire *E*, which comes from one pole of the battery *Z*, and projects through the bottom of the vessel into the mercury. If now another wire, attached to the other pole of the battery, passes down vertically into the mercury as *GH*, a communication is established between the extremities of the battery, and the current flows. The apparatus is so adjusted, that when the cup is nearly filled with mercury the free pole shall float nearly upright upon its surface. When the circuit is completed, this pole begins to revolve about the upright wire, the centrifugal force enlarging the circle of revolution till an equilibrium is established between it and the resistance of the mercury. The direction of the motion depends on the direction of the current and the magnetism of the free pole. If the current descends, the north pole of a magnet revolves from left to right. With a view to diminishing the resistance to the revolution from the
Fig. 138. mercury, another way has been devised for making a current act on a single pole of the magnet. *NS*, is a magnet, supported by its centre, which is bent, upon a pivot at the top of a rod, set into the base of the instrument. Near the bottom of the magnet is a small loop, running round this upright wire, that keeps the magnet in a vertical position while it moves. At *C* and *Z*, the contacts with the ends

of the battery are formed. If C is the positive pole, the current will pass down the wire CE, so as to dip into the small cup of mercury which is firmly fixed on the centre of the magnet; thence a bent wire goes into the outer cup of mercury, composed of a hollow double cylinder, in which the magnet runs and between the sides of which the bent wire remains during the motion. If mercury is poured into this cistern so as to touch the wire, the current flows on to Z; the circuit is completed, and the magnet revolves around the wire.

In the last experiment, if another current is sent parallel to the pole S, up to E, but in an opposite direction to the first current, the opposite currents acting on opposite poles will conspire in their effect and give a more rapid rotation than the single current; and thus both poles of the magnet will contribute to the motion.

222. From the universal principle in Mechanics, that action and reaction are always equal, whatever motions are produced by a fixed conductor on a movable magnet, we might expect that corresponding movements would result, when the magnet is fixed and the wire is movable; and this we find to be the case. The original experiments on the deflection of the needle may be repeated in this way and the conducting wire be turned round while the magnet is fixed. In either case, the needle and conductor come at last into the same relative position. We might expect, accordingly, that if a magnet and conductor were properly arranged to produce the tangential forces, and if the magnet were fixed and the conductor were movable, we should reverse the first experiment of revolution and make the wire move about the magnet. This has been done by the following piece of apparatus.

It consists of a glass cylinder, AB, mounted upon an iron wire Fig. 139.
EF, which is firmly fixed in the centre of a wooden stand. A cup G is placed at the top from which a copper wire passes down, having a loop e. The soft iron bar EF projects above the bottom of the glass cylinder, and is rounded at its top. Mercury is placed within the lower part of the glass cylinder and also in the cup at the top. A platinum wire, having a loop formed at its upper end, is loosely hung to the loop above, and touches the surface of the mercury within the glass cylinder. Upon making a communication with a voltaic battery, by means of two connecting wires

placed in the mercury of the upper and lower cups, and bringing a magnet into contact with the lower part *F* of the iron wire, which projects below the wooden support for that purpose, the platinum wire will begin to revolve around the magnet in a direction depending on that of the current and on the pole of the magnet which touches the soft iron. By reversing this current or the pole of the magnet, the direction of the motion will be changed; but if both are reversed at once, the motion continues the same, as might be expected from the general principles of electro-dynamic action.

223. If, instead of submitting a conducting wire to the action of one magnetic pole only, it be so arranged as to be exposed to the influence of both poles, a vibratory instead of a rotatory motion
Fig. 140. ensues. Let a light wire, *W*, be suspended from a brass rod connected with the binding screw* or cup of mercury *C*, so that its lower end just dips into a cavity cut out in the base of the instrument, filled with mercury, and connected by a wire with the cup *Z*. Let a horse-shoe magnet be placed, as shown in the figure, and connect *C* with the copper, and *Z* with the zinc plate of an electrometer. The current of positive electricity will descend *W*, and, being acted upon by both poles of the magnet, the wire will tend to rotate to the right round the austral pole *N*, and to the left round the boreal pole *S*. As it cannot obey both these forces at once, being opposed in direction, it takes an intermediate course, as might be expected from the principle of the composition of forces, and is thrown forward out of the mercury in the direction indicated by the arrow. The connexion with the battery being thus broken, the wire by its gravity falls into the mercury again, and is again thrown out; and thus it will continue to oscillate backward and forward as long as the apparatus remains in order. If the direction of the current or the position of the poles of the magnet be changed, the oscillation will be backward, or in the opposite direction.

Fig. 141. If the electric current be made to pass through a spur-wheel, *W*, instead of a wire, a rotatory movement between the poles of the magnet ensues, each spoke of the wheel as it dips into the mercury

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* It will be found convenient in experiments to dispense as far as possible with the use of mercury. Binding screws are on this account preferable for making a perfect contact between different parts of the circuit.

becoming the momentary channel of communication and answering to the conducting wire of figure 140. It is of course thrown out for the same reason as in that case, and another spoke dipping into the mercury is in turn thrown out in the same direction, and thus the vibration is changed to a continued movement in this direction. If the direction of the current or the poles of the magnet be altered, the wheel will rotate in the opposite direction. If both be changed at the same time, no effect will be produced on the direction of the motion. The direction of the current is easily altered by making the electrepeter a part of the circuit. The principle holds, whatever the number of spokes in the wheel. Hence we may substitute for a spur-wheel a disc, or complete circumference. From the Fig. 142. greater number of touching points, we might expect in this case a greater velocity. But the increased friction seems to more than make up for this advantage.

224. We have next to describe a piece of apparatus by which a magnet is made to rotate round its own axis. Let *NS* be a flat bar Fig. 143. magnet supported in a vertical position by an upright metal wire *E*, fixed in the base of the instrument, and having a hole in its centre, containing an agate cup, to receive the lower pointed end of the magnet. Its upper end turns in another hole, made in a vertical screw, which is turned by a milled head *M*, so as to admit of adjustment. A wire passes from the end *S* of the magnet into a cistern of mercury *H*, and thus connects the magnet with the cup *Z*. Another cistern is seen at *N*, which has a hole in its centre large enough for the magnet to turn in it. Another wire passes from the middle of the magnet and dips into the mercury of this cistern and thus connects the middle of the magnet with the cup *C*. Now if the cups *C* and *Z* are connected with the electromotor, the current will traverse the lower half of the magnet, and the magnet will turn rapidly round its axis. If we could consider the current as traversing only the axis of the magnet, this case would reduce itself to that of Fig. 138, where the magnet revolves about the conductor; in this case the axis of the magnet being itself the conductor, the motion is about this axis, and the revolution becomes a rotation. Or if we could suppose the current to traverse only the surface of the magnet, this case would be reduced to that of a conductor revolving round a magnet. We are not at liberty, however,

to adopt either of these simple suppositions. We must consider the currents as traversing every part of the magnet, so that the explanation of the resulting motion would require a more careful analysis of the question than can be admitted into this elementary discussion of the science.

Having succeeded in making the magnet revolve on its own axis, it was next to be seen whether a wire could be made to do the same, when a current was flowing through it. As in the former case it was necessary to make the axis of the magnet the conductor, so here means must be devised of making the axis of the conductor
Fig. 144. magnetic. For this purpose, we take a horse-shoe magnet *NS*, placed in a vertical position, with vertical troughs *AB* screwed upon its legs; a light wire frame, supported by a fine steel point on each pole of the magnet, is so arranged that its vertical branches just touch the surface of the mercury in *AB*. Each of the wire frames terminates in a cup containing a drop of mercury, into which the ends of the cross wires from *E* dip. Connect the cup of mercury *E*, by means of a wire, with the positive plate of the electromotor, either directly or through the electrepeter, and let the wires *Z*, *Z'*, coming from the circular troughs *A*, *B*, be *both* connected with the negative end of the battery. Under these circumstances, a current of positive electricity will pass to the cup *E*, from the electromotor, and there being divided into two portions, will descend the vertical branches of the wire frames, and reach the troughs *A*, *B*, leaving the apparatus by the wires *Z*, *Z'*. As soon as the current is in motion, the wire frame, suspended on the north pole of the magnet, begins to rotate rapidly in a direction from left to right, and that round the south pole in a contrary direction, from the *re-action* of the fixed magnet on the movable conducting wires. If the direction of the current be changed by turning the bars of the electrepeter, the motions will be each in an opposite direction. If we connect *Z* with the positive, and *Z'* with the negative end of the battery, the current will run *up* from *A* to *N* and down from *S* to *B*; the direction being opposite and the poles of the magnet being opposite, the direction of the motion in this case will be the *same*, and the two wire frames will revolve round in the same direction. This experiment is slightly modified by using, instead of the wire frames seen on the figure, pieces of wire bent into a heliacal coil like a

cork-screw, and resting by one end on the extremity of the magnet and dipping by the other into the troughs of mercury *A*, *B*. In this case the magnet itself makes a part of the circuit. Sometimes instead of the wire frames, hollow cylinders have been hung over the poles of the magnet, spurred at the bottom, and thus dipping into the mercury.

It has been determined by experiment that the circumstance of the magnet and conductors being one body does not change the result. Thus, let the magnet, *NS*, be loaded at its lower end with Fig. 145. a platina weight, and fixed at its upper end on a piece of card or wood, having two branches of a strong wire, *WW'*, attached to it, in such a way that the extremities may just dip into the mercury with which the vessel *M* is filled. The whole will float in a vertical position in this mercury. The battery-current is then transmitted through the wires, *WW'*, by means of the cups *C* and *Z*, and the wires turn round the magnet carrying the magnet with them. The effect is the same, therefore, whether the magnet is at rest or in motion. In this experiment the resistance of the mercury diminishes very much the motion. This is avoided by another form of apparatus. A magnet, *NS*, rests on an agate cup *A*, and runs at Fig. 146. the top into a cavity *E* of a rod which is firmly fixed on the frame of the instrument. A bent wire passes from this rod and dips into a cistern of mercury which the magnet carries. Two wires, *WW'*, pass from this cistern into another which surrounds the middle of the magnet, and which connects with the cup *Z*. This cup receives one wire from the electromotor, and the other goes to the cup *C*. When the circuit is completed, the whole movable part of the apparatus begins to rotate.

225. It has been found that the stream of electricity which is passing through the voltaic battery itself, from its negative to its positive pole, exhibits the same electro-magnetic properties as it does while passing along the wire which completes the circuit outside: for a magnetic needle laid on the battery will be deflected in both cases according to the same law. Now, on account of the equality of action and reaction, it would be reasonable to infer that if the magnet were fixed and the battery movable, a corresponding motion would take place in the latter. This could not be effected with a compound battery of any size; but by reducing it to a

single element, making it as light as possible, and supporting it on a single point in an agate cup, we confirm the conjecture by actual experiment. The most approved form of apparatus for this pur-
Fig. 147. pose is thus constructed. It consists of a horse-shoe magnet *NS*, firmly fixed to a stand *M*, at its bent part. The two ends of this magnet are made round, and have small holes in the centre, at the bottom of which agate cups are placed; in which pointed wires, sustaining the battery, are supported. A double cylindrical copper vessel, having a bent copper wire attached to opposite points of the top of the interior cylinder, is in this way hung over each pole of the magnet. A hollow cylinder of zinc, furnished with a similar bent wire and a vertical pointed wire at its centre, is placed within the double cylinder, and is supported in a cavity *C*, on the upper part of the bent wire coming from the copper vessel. A mixture of sulphuric and muriatic acid with water being poured into the space between the double copper cylinders, voltaic action commences, and the two vessels of copper and the two cylinders of zinc begin to rotate about the poles of the magnet. The vessels on the opposite poles of the magnet move in opposite directions, and the zinc vessels move in an opposite direction to the copper vessels on the same pole. The weight of the vessels and the solution will cause so much friction as to defeat the experiment, unless the suspension is very delicate, and the voltaic action strong. This resistance is very much diminished by the following recent modifi-
Fig. 148. cation of the apparatus. Instead of the double copper cylinders and the zinc cylinders, we may attach to the bent wires at each end a piece of copper and zinc, so that its edge shall be in the direction of the motion. These plates of metal dip into a solution of acid and water which is contained in vessels *MN*, attached by binding screws to the magnet. The resistance which the liquid makes to the motion is less than that which arises from the greater weight of the mixture and the large cylinder.

226. The motions of revolution and rotation, produced by the tangential action of the pole of a magnet, is exemplified in fluid, as well as in solid conductors. Mercury, for example, while conducting a current of electricity, is made to exhibit these motions. By immersing the points of the positive and negative wires of the battery into a basin containing mercury, a magnet, held either above

or below the line of communication, will cause the mercury to revolve round the points from which the currents diverge. This motion may be rendered more evident by covering the mercury with a very dilute acid solution, which occasion the disengagement of bubbles of air which are moved along with the mercury. The same phenomenon may also be exhibited in the following manner. If the positive wire terminate in a steel point, which is dipped into mercury contained in a shallow basin, so as to carry into it an electric current, which, passing in radiating lines through the mercury, is received by a copper ring surrounding the steel point, and so transferred to the negative pole, — by placing the pole of a strong magnet underneath the basin, immediately below the steel-pointed wire, the mercury will be seen to revolve rapidly in a vortex round the point from which the currents diverge. The revolution is in the contrary direction, when the direction of the current is reversed, or the opposite pole of the magnet is applied. The effect of rotation is seen in the depression, caused by the centrifugal forces, of the slight elevation which is produced in the mercury at the points where the wires are introduced by the action of that part of the current in the wire upon that in the mercury: for we shall see presently that currents act upon each other as well as upon magnets. Tin in a state of fusion will answer the same purpose as the mercury, and indeed any good liquid conductor. Water has been made to rotate in this way: by pouring it into a hollow double cylinder of glass and sending the current through it: the vessel itself remaining stationary.

227. The earth acting like a magnet, it was natural to inquire what influence would be produced by terrestrial magnetism on a conducting wire. The nature of the case precludes the idea of any motion on the magnet itself; but the re-action will show whether any perceptible action takes place. To this end we take a frame *ABC*, Fig of copper wire, and fix it to a piece of wood *D*, which moves on a pivot, so that the two ends of the wire may dip into two concentric cells, filled with mercury and connected by wires passing through the base *E* to the screws *C*, *Z*. If *C* be connected to the positive and *Z* to the negative end of a battery, a current will traverse the frame in the direction of the arrows. The rectangle being freely suspended in this way and uninfluenced by any opposing cause, it

will be acted on by the earth's magnetism and assume a definite position; which it will, if sufficiently delicate, regain when disturbed from it by any applied force. That face of the rectangle through which the positive current is moving, in the direction of the hands of a watch, always turning towards the south, whilst the other or that in which the positive current of electricity appears to move from right to left, or opposed to the hands of a watch, will assume the properties of an austral pole, and will consequently point to the northern hemisphere of the earth. Thus in the figure, that face of the rectangle *ABC*, which is there represented, will regard the south pole of the earth; the current of positive electricity moving in it from left to right. If the conducting wire be bent into a circular or other figure, it will present the same phenomena as the rectangle; the shape not influencing its properties.

If instead of using a single fold of wire, as a circle or rectangle, the principle of the multiplier be applied and several convolutions employed, the polar phenomena will be proportionally increased. This may be very satisfactorily shown by means of the little apparatus, constructed by De la Rive, consisting of a plate of
Fig. 150. zinc, *Z*, about an inch square, placed between the folds of a bent plate of copper of the same size, like Wollaston's voltaic element before described. A piece of copper wire, covered with silk, is soldered to the copper plate, and after being twisted into about twenty circular coils, *B*, kept close together by means of thread, is fixed by its other extremity to the zinc plate. This apparatus is placed in a shallow wooden cup, *A*, filled with dilute sulphuric acid, and, on allowing it to float in a vessel of water, the whole will, after a few oscillations, arrange itself according to the magnetic meridian, the plane of the circle being at right angles to it. This is explained by considering that the action of the acid on the plates *C*, *Z*, developes sufficient electricity to cause the coil *B* to present magnetic phenomena; that aspect, in which the positive current appears to be moving from left to right, regarding the southern hemisphere of the earth. On presenting a magnet towards the coil of wire *B*, whilst the apparatus is in action, attraction and repulsion will ensue, as if the wire itself had really become a magnet.

The coil of wire used in the preceding experiment may be regarded, as long as the current traverses it, as a *flat* magnet; but if

the convolution, instead of being nearly in the same plane, be drawn out, so as to represent a long helix, its apparent magnetic properties Fig. 151. become much more distinct. Let a wire, covered with cotton or silk, be coiled on a glass tube in a direction from left to right, forming a right-handed helix, and be supported on a pivot, as at *C*, its two ends, *D*, *E*, hanging down, and just dipping into two concentric troughs of mercury, connected with the screws *K*, *Z*, as in the support of the rectangular conductor before described. On connecting these screws with the two plates of an electromotor, the electricity will traverse the heliacal conducting wire, which, after a few oscillations, will arrange itself in the magnetic meridian ; that end in which the positive current moves from left to right, pointing towards the south pole of the earth. The two extremities of this helix are respectively attracted or repelled by the poles of a magnet as long as the electric current traverses it, as really as if it were a permanent steel magnet. Ampère, to whom we are indebted for the knowledge of the properties of this and other heliacal conductors, has termed it the *electro-dynamic cylinder.*

Electro-Magnetism.

228. We are now brought by the natural development of the subject to that part of the new science of electro-dynamics to which the name of Electro-Magnetism properly belongs. The coils of wire, of which we have been just speaking, possess magnetic properties; they place themselves under the influence of the earth's directive power as ordinary steel magnets would do. This fact of the magnetic properties of a wire conducting electricity is shown in its elementary form, by taking a thick curved wire and connecting it to the ends of an electromotor, so that the current may traverse it ; divide it in the middle, leaving about an inch between the divided portions, and reconnect them by means of a piece of fine copper wire. On dipping this thin wire, whilst the current is passing through it, into iron filings, they will be attracted and adhere to it, as if it had suddenly acquired magnetic properties. The filings will be attached to the wire in the form of rings, about one-twentieth of an inch apart, and will drop off the instant the current ceases to pass. If a small

steel needle be placed at right angles across a chain or wire, through which a charge of common machine electricity is sent, it will be made a permanent magnet.

Soon after the discovery of Oersted was made known in Paris, Arago observed, that the conducting wire of the voltaic apparatus attracted iron filings, like the magnet, and that these filings detached themselves, immediately upon the communication being interrupted. This phenomenon is not to be attributed to the ordinary action of electricity, since the experiment does not succeed with the minute parts of any substance not magnetic. Moreover, he perceived that the voltaic wire communicated to the iron only a transient magnetism, while it imparted to steel a durable magnetism; that the magnetizing takes place in a direction perpendicular to that of the current, that is, in a direction which the needle tends to take when placed above or below the current; and that two parallel steel wires, forming each a right angle with the conducting wire, and placed at equal distances from it, on opposite sides, acquire the same degree of magnetism.

The magnetic properties of the conducting wire can be next tested by seeing whether it will induce magnetism in soft iron or steel as ordinary magnets will do. Arago, by placing a steel
Fig. 152. needle in the helix, imagined by Ampère, obtained magnets, the poles of which were reversed by repeating the experiment with a current in the opposite direction. By introducing a steel wire into several helixes, formed with the same conducting wire, turned alternately in opposite directions, he produced consecutive points. Placed without the helixes, the steel wires were magnetized with difficulty. They ought also, in this last case, to become magnetized in a reverse manner. Arago performed these experiments at first with a continued current; he showed, afterwards, that common electricity, transmitted from a Leyden jar or battery through the same helixes, in like manner magnetized the steel wire.

In these experiments, where steel is used, it is important that the electricity should have a high tension; so that they only succeed when powerful galvanic batteries or a charge of machine electricity is employed. But if we take a piece of soft iron and surround it by a coil through which a feeble voltaic current is passing, it is made magnetic; in this case, however, the magnetism is transient

and disappears when the current ceases to flow through the wire. As in all these experiments the electricity does not enter the iron, but merely passes round it in the coil, we learn that an electric current traversing a wire possesses the property, common to steel magnets, of inducing magnetism in iron or steel bars brought within its influence, and placed with their axes at right angles to the direction of the current. This induction takes place, as in the ordinary ways of magnetizing, through glass and any other unmagnetic substance, with only that diminution which would arise from an increase of distance. If the bars be not placed at right angles to the conductors, the magnetism induced is proportionally weaker, and at length ceases altogether.

229. If a bar of soft iron be bent into the shape of the letter U, Fig. 153.
and be covered with *several series* of folds of copper wire, insulated by being wound with cotton or silk, and a current of electricity be transmitted through the wires, by connecting their ends to the plates of an electromotor, the intensity of the induced magnetism can be made very great. On placing a smooth bar of soft iron, like a keeper, opposite to the two ends of this bent bar, it will be attracted and remain firmly adherent; and in some cases an immense weight may be suspended to it without separating it. This is what is called the Electro-Magnet; the magnetism is induced, not by the contact of common steel magnets, but by the magnetic properties of the surrounding conductor. Magnets of this sort have been made capable of supporting a ton weight. Such a one belongs to the apparatus of Harvard University. In these large electro-magnets, it is important that the wire should be broken into several pieces, and the different ends attached to the electromotor; otherwise the force of the current and the inducing power will be materially diminished by the great length of the circuit. The strength of magnetism in electro-magneto, far exceeds that which is found in steel magnets of the same size, even when magnetized to saturation. A temporary magnet has been made capable of supporting two hundred pounds weight by means of a single voltaic element, consisting of two plates, less than one-fourth of an inch square, soldered together. As the surface of the iron appears to be the only part called into action in this process, a great economy of materials will be gained by cutting into the ends of the iron a few inches, and Fig. 154.

winding the wire around each of the projecting blocks of metal. The same length of wire and iron will bring into activity a much larger amount of surface, and the power will be very much increased when all the other circumstances remain the same. It is remarkable, that if the contact with the battery be broken, whilst the poles of the electro-magnet are unconnected with each other, the induced magnetism will, if the iron be very soft, entirely vanish in a short time. But if the poles be connected by a bar of soft iron, before communication with the source of electricity is interrupted, a considerable magnetic intensity is left in the temporary magnet, and is permanent so long as the poles are thus connected, disappearing only on the removal of the piece of iron adhering to them.

Fig. 155. Let *a*, *a*, represent two systems of wire wound compactly into a cylindrical form, each consisting of five distinct layers or lengths, protected by brass casings, (split on the under side,) and ivory heads *c*, *c*, *c′*, *c′*; *b*, *b*, are two curved bars of soft iron which slide easily into the hollow cylinders, so as to meet; *o*, *o*, are handles for pulling, consisting of ball and socket joints at *o*, *o*, to prevent wrenching or twisting. The terminations of the coils pass to the cups *C* and *Z*, to be connected with the battery. The attractive force manifested in this apparatus at the centre of the helixes, is much greater than when an armature is applied at the extremities. Suppose a magnet
Fig. 156. *N*, *S*, to be supported upon a stand in a horizontal position, and a circular coil of wire to be suspended from a pivot at *A* in such a manner as to allow it when moving on that point to pass on to one of the poles of the magnet. If a current is sent through it in such a direction that the face turned towards the pole of the magnet has an opposite polarity to that of the magnet, the attraction will bring the ring of wire on to the pole. It is arranged that by this motion the connexion with the battery shall be broken. This is done by the wire *W* dipping into the cup of mercury at *M*. Then the ring will be brought by gravity into the vertical again; the current will flow once more, and a vibrating motion may thus be sustained. If another ring be suspended in front of the other pole of the magnet, we may exhibit the motion of two coils, one passing off its pole when the other is coming on.

230. On account of the ease with which the poles of an electro-

magnet are changed simply by altering the direction of the current, they can be readily applied to the production of a continuous motion. Let *NS* be an upright horse-shoe magnet; now if a common steel Fig. 157
magnet were to be placed between these poles at right angles to the position of the bar *A*, one pole of this magnet would be attracted by *N*, and the other pole would be attracted by *S*, and both together would bring the small magnet into the position of *A* in the figure, or in the line which connects *NS*. The inertia of the bar would at first carry it a little beyond the position of equilibrium, and if at this moment the poles of the bar could be changed, repulsion taking place between the extremities which first attracted the bar would continue its motion round half a circumference farther. If the poles were again changed, and so on at every half revolution, we should have a revolution of the bar between the extremities *NS* of the horse-shoe magnet. Now this change of poles, which is impracticable with common steel magnets, is readily effected in an electro-magnet. Suppose then the bar *A* to be wound with a coil of insulated copper wire, the two extremities of which come down and touch the mercury contained in a circular trough *B*, which is divided into two cells by a transverse slip of wood. On account of the capillary repulsion between the mercury and the wood, its level can be so far raised above the wood without overflowing, that the wires, when short enough to pass freely over the wood, will still dip into the mercury. Let now the wires *CZ*, which come from the two separate parts of the basin, be carried to the extremities of the electromotor and attached, the positive current will pass into that half of the basin which is connected to *C*: and the negative current into the other. As the ends of the wire, which come from *A*, dip alternately into these two basins, the poles of the small electro-magnet are charged each half revolution, and it is only necessary that the partition should be properly situated in order that this magnet, which is delicately balanced upon a pivot, should turn round with great rapidity. During the action of this apparatus, a loud humming noise, often amounting to a loud musical sound, is excited by the rapid vibrating motion assumed by the fixed magnet during the rapid revolution of the electro-magnet. This musical sound is particularly observed, when the instrument is supported by three levelling screws on a smooth table. As the wires pass through the mer-

cury of the cisterns, in this form of apparatus, it is dashed out or thown across the wood partition, so that either the level sinks below the wires, or the two basins are connected together. In either case, the motion will soon cease. This is prevented by another mode of changing the poles of an electro-magnet, which dispenses with mercury entirely and is always to be preferred to the old way just described. The apparatus by which this is done is very simple, and is called a pole-changer. We may suppose then the cup of mercury *B* to be removed, and the electro-magnet to be supported on a pivot as before: the outside of this pivot receives two metal cylindrical portions, not quite touching at either side when wrapped around the pivot, but separated by a small interval which is filled with some
Fig. 158. non-conducting material. One end of the coil which passes round *A* is soldered firmly to each of these cylindrical pieces. Two slender springs, supported on the poles *N* and *S* of the magnet and coming from the two extremities of the electromotor, press gently upon the pivot. Now as the magnet turns, the same sides of it will come in contact with the two spring wires alternately every half revolution, and hence the positive current will sometimes enter at one end of the coil, and sometimes at the other. If the soft iron bar be removed, and nothing but the coil remain, that also will rotate round the pivot, illustrating by a new experiment the polarity of a coil of wire through which a current is passing. Instead of
Fig. 159. a helix, we may use a flat coil, or a rectangular frame of wire, sup-
Fig. 160. ported between the poles of the steel magnet, and the same rotation is produced. It is necessary in all cases where the pole-changer is used that the divisions of the cylinders should occur at such places that the poles may be changed just after they have passed the ends of the steel magnet. When we reverse the wires which communicate with the battery, we alter in all these cases the direction of the motion.

If the electro-magnet be about four or five inches long, it will rotate by the magnetism of the earth, independent of any steel magnet in its neighborhood. This is a very curious experiment. In order that it may succeed, care must be taken to place the bar in the magnetic meridian and allow the electric current to traverse the wire coiled round it in such a direction that the poles of the

temporary magnet may be the same as are repelled by the hemisphere of the globe to which they are directed.

231. In all these examples of electro-magnetic rotation, the movable magnet has been furnished with the coil, and the steel magnet has been fixed. But the reverse experiment may be shown. The horse-shoe magnet may be made of soft iron, and covered with a coil of insulated copper wire, the extremities of which are joined to the two ends of the electromotor. Let *MM'* represent such an electro-magnet: let *a* be an armature of soft iron; *e* an upright stem of brass, upon which the armature turns, and which is braced by a disc of wood at *b*; *c* is one termination of the coil of wire, pressing on the axis; *d* is another conducting spring, passing through the disc *b* into the cup *n*, and thence to the battery. The other termination of the magnet coil passes to the cup *p*. On the axis, at the height of *cd*, is a silver break piece, on which *c* constantly presses, and *d* only part of the time. The break is so arranged that *d* comes in contact with the silver projection when the magnet is a little beyond the right angle to the line which connects the poles *MM'*, and that it leaves it again before the armature has quite come round to this line. The motion is here produced by attraction alone. If the magnetism of *MM'* were constant, the armature would be drawn to the extremities of the poles and there remain; but the circuit from pole to pole of the battery is only completed during a part of the revolution, as the armature is moving towards the poles *MM'*, and ceases before it has quite reached them, so that the impulse which it receives at this time carries it round to the place where the circuit is completed again, the magnetism of *MM'* restored, and another impulse given to it to produce similar effects. If the magnetism were not withdrawn from *MM'* the armature would not be able to leave the poles after reaching them. The velocity in this apparatus is exceedingly great. If *a* be a small magnet instead of a bar of soft iron it would be necessary to have the current cut off from the electro-magnet all the time except when the same end of *a* was approaching the same pole of *MM'*; in this case the velocity would not be so great, but the experiment would be more exactly the reverse of that in which an electro-magnet rotates between the poles of a steel magnet. When *a* is a soft iron armature, it is to be observed

that magnetism, as we consider it in steel bars, is entirely excluded from the case; the motion is produced by the mutual action of the current upon the soft iron. As a still further modification of electro-magnetic rotation, we may mount two semicircular magnets on parallel axes, so that their poles will just pass by one another. The coil of the upper one communicates through the lower with the battery cups *C* and *Z*. By means of a pole-changer at *D*, the current in the lower magnet is kept always in the same direction and acts therefore like a permanent magnet. By means of another pole-changer at *P*, the current in the upper magnet is changed twice every revolution. The upper magnet therefore, rotates as on Fig. 158, and the lower ones being also movable, will turn by the re-action in the opposite direction. A horizontal section of the pole-changer used in all these experiments, may be seen on the next
Fig. 162. figure. *SS* are two cylindrical pieces of silver, fixed to opposite sides of the axis of motion, but insulated from it and from one another; one end of the coil running through the apparatus is soldered to each of these pieces; and spring wires, *WW*, connect the cylinders themselves with the battery. As the axis turns, the same wire presses in succession upon the opposite silver pieces, and sends its current into the corresponding end of the coil.

232. Electro-magnets possessing all the properties of common steel magnets, with the additional advantage of greater strength, all the experiments of magnetism or electro-dynamics which are performed with steel magnets will succeed even better with artificial magnets. By having the direction of the coil changed, we may produce consecutive points in an electro-magnet. If we take a bar of soft iron and wind it in opposite directions from the centre with insulated copper wire, when a current is sent through the coil, the two extremities of the bar will have the same polarity, and there will be two opposite poles at the middle.

233. The great discovery of Oersted, which has so much extended the limits of physical science, has appeared to many the promise of a new career in practical mechanics. The distinction between the electro-dynamical force and all others yet employed is that the point of application is at the place where the force is generated. The force is not applied to a machine; it is in the machine, and corresponds more nearly to the living mechanism of the human body than any thing else.

How far this is to be an advantage, and to what extent this force, so strange and captivating in a scientific view, is to become serviceable in mere mechanics, are not questions now and here to be discussed. So far as the arts are concerned, the mode of application is the chief circumstance. The immense usefulness of steam is not to be attributed to the discovery of a new motive-power, but the great improvements that have been made by Watt and others in the application of it; and it is impossible to say now that the same happy means may not do as much for the new forces, although at present, and measured by the great and simple results of steam power, they seem inefficient. Of the various models of machines, moved by electro-magnetic power, which have been constructed since the discovery of the new agent, we select for description one of the most simple in its form and neat in its operation. Let *aa* be two electro-magnets, firmly secured to Fig. 163.
a wooden base; *bb* are armatures of soft iron connected with a shaft *d* by stout brass arms. The motion of the armatures up and down, by the alternate attraction of the electro-magnets, is communicated to a reciprocating beam, to one end of which, by means of a crank, a balance wheel *m* is attached. The break piece by which the current is sent successively into the two coils, is placed on the axis of the balance wheel. Three conducting springs come up from the base, and press upon this axis, one constantly and the other two by turns. *Z* and *C* are cups for connecting with the electromotor; the dotted lines on the base represent the wires which run under the base as connexions between different points. It is very easy so to arrange the break piece that the current shall begin and cease to flow through each coil at the proper time. Two small plates, or a simple voltaic element, will set this engine in very rapid motion.

Voltaic Induction and Magneto-Electric Induction.

234. We pass now from electro-magnetic induction, or the induction of magnetism by electricity, to magneto-electric induction, which is the induction of *electricity* by a *magnet*, and voltaic induction or the induction of one current of electricity by another. Of all the numerous and successful researches made by Faraday, in the different departments of electrical science, none are of greater importance

or more worthy of deep attention and study than these. The following is a brief generalization of the facts of this wonderful branch of electrical science.

235. Let there be two wires, covered with silk, so arranged about a common support as to form two helixes in a manner parallel Fig. 164. to each other through their whole extent. This being supposed, if we connect the two extremities of one of the wires with the poles of a powerful voltaic apparatus, and connect the extremities of the other wire with a galvanometer, we remark, 1. that *a current takes place in the wire of the galvanometer in a direction opposite to that of the generating current;* 2. that *the current ceases forthwith, since the galvanometer resumes its first position;* 3. that *a current in a reverse direction is manifested in the galvanometer, at the moment the communication is destroyed between the generating wire and the voltaic apparatus.*

Several other experiments are suggested by the above facts. If we substitute a helix for the galvanometer, and place a steel wire in it, it will be magnetized in one direction the moment the communication is established; but there will be no magnetism communicated, if we place the steel wire and withdraw it during the continuance of the generating current; lastly, it is magnetized in a reverse manner, if we introduce the steel wire while the generating current is in action, and allow it to remain till the moment of interruption.

236. If a wire connected with a galvanometer is *brought near* to a wire communicating with a voltaic apparatus in action, there is produced in the former a current in a direction opposite to that of the latter; whereas, the current takes place in the same direction, if we *withdraw* the first wire from the second. If the first wire is kept in the same position, no current is manifested.

The substitution of a magnet for the generating current of the voltaic apparatus, gives rise to phenomena analogous to the preceding. If, for example, we surround the armature, consisting of soft iron, of a powerful horse-shoe magnet with a copper wire covered with silk, and communicating with a galvanometer, we find that the application of the armature to the magnet causes a deviation in the galvanometer, in a direction opposite to that produced by the current which puts the armature in the state to which it is brought by

the magnet. If we withdraw the armature from the magnet a deviation in a contrary direction is manifested. During the contact the galvanometer is not affected.

Magnets ought evidently, according to this last fact, to act upon helixes. Indeed, if we introduce a magnet into the interior of a helix, whose two extremities communicate with a galvanometer, it will be seen, on approaching it suddenly, that a deviation takes place in the galvanometer. If we withdraw it, a deviation in a contrary direction is observed. If we bring the magnet to the middle of the helix, there is no deviation. Lastly, the galvanometer exhibits a deviation the reverse of the first, when the magnet is withdrawn at the extremity opposite to that at which it is introduced.

In all these cases, the galvanometer does not indicate a current when the magnet is at rest. It may be supposed, that, if we were to place a piece of soft iron in the helix, the effects manifested upon the approach of a magnet and its removal would be increased; this is, in fact, what is found to take place.

Wind round a hollow cylinder of pasteboard a few feet of insulated copper wire, the ends of which are attached to a delicate galvanometer. If a long bar of soft iron is inserted into this cylinder, and alternately brought to and removed from the position of the dipping-needle, the bar will in succession receive and lose magnetism by induction from the earth; and these changes in the magnetic state of the bar will produce, the moment they occur, a temporary current in the helix, as will be seen by the motion of the galvanometer.

A second coil of wire is by no means necessary for the development of an electric current; a single length of insulated wire, coiled into a compact helix, has an induced current excited in it in one direction, on *making* connexion, and another in an opposite direction on breaking connexion, with the battery or other source of electricity. These induced currents, like those before described, are of momentary duration, and are always related in direction to the primary current; they may be considered as arising from the reaction of the primary current traversing each fold of wire on the electricity naturally present in the adjoining folds. In this manner is explained the appearance of a vivid flash of light, observed on *breaking* the connexion with a small electromotor by means of a

wire folded into a compact coil; whilst scarcely the faintest spark is perceived when a short wire or long *unfolded* one is used. If connexions be made and broken by means of a cup of mercury, the brilliancy of the light is increased by reflection from the bright surface of the fluid metal, as well as from the combustion of the latter by the discharge. If the wire be folded round a bar of iron, the induced magnetism in that will increase the intensity of the secondary current and consequent splendor of the spark; on breaking contact with the source of electricity. On this principle are explained the vivid sparks seen during the rotation of the electro-magnet and flat coil, when a cup of mercury is used for a pole-changer; and during the vibration of the wire between the poles of the horse-shoe magnet and the revolution of the stellated wheel, and elsewhere. In many cases, the heat evolved is sufficient to inflame ether or gunpowder, placed on the surface of the fluid metal. Connect one end of a compact helix to the end *Z* of the battery, and attach to the other end *C* of the battery a clean steel file; draw the other end of the wire over the surface of the file so as to have the contacts made and broken with great rapidity, and a succession of reddish sparks, attended with the light arising from the brilliant combustion of the steel, will ensue. If a piece of gold leaf or silver be placed on the end of the wire which makes and breaks the connexion, they will burn with their characteristic light.

Fig. 165. Let two hundred or three hundred feet of insulated copper wire be coiled on a hollow wooden reel, about two inches long, and furnish each end of the wire with cylindrical handles, *A*, *B*, which may be plated with German silver. Grasping these cylinders with the hands, immerse *C* in a cup of mercury, connected with one plate of the electromotor, and *Z* in a second connected with the other plate; suddenly withdraw one of them as *Z*, and the secondary current thus excited, in completing the circuit from *A* to *B*, rushes through the arms of the person grasping them, producing a severe electric shock. If the hands be moistened, to render them better conductors, and the connexion be made and broken with the electromotor, by connecting *C* to one plate and drawing *Z* over the surface of a file connected with the other plate, a rapid succession of very painful electric shocks will pass through the arms and chest of the operator. By placing in the hollow axis of the reel a bar of

soft iron, or, still better, a bundle of soft iron wire, *EF*, the intensity of the induced currents, as shown by the vividity of the sparks and the strength of the shocks, is proportionally increased. The intensity of this secondary current far exceeds that of the primitive current flowing from the electromotor. With a single pair of plates, the latter would be quite insensible so far as physiological effect is concerned, though the former would give a severe shock.

237. We have seen that these secondary currents can be induced in a wire, by bringing a magnet up to it or removing it back. More generally, if we take a disc of copper, suspended by its axis so as to turn between the two poles of a horse-shoe magnet and just dip into a cistern of mercury, and instead of connecting the cups, *C*, *Z*, with the electromotor fix them to a delicate galvanometer, and then cause the disc to revolve rapidly on its axis by an impulse with the finger, the inductive action of the magnet on the revolving disc will generate a current in it that will show itself in the galvanometer. We have here another instance of the law of action and re-action. In the first experiment with this disc, *it* was set in motion by a current; here the *electricity* is set in motion by the motion of the disc, mechanically produced. Thus was Faraday conducted by his experimental researches in electricity to a generalization, if not a complete and satisfactory explanation, of the facts, some years before noticed by Arago and others, and which hitherto have defied all attempts at a solution. The strange phenomena, in regard to the influence of magnetism on motion, made known by this distinguished philosopher, are briefly these. They consist of two kinds; the first relate to the influence of bodies at rest upon a magnetic needle in motion; the second, the influence of bodies in motion upon the magnetic needle at rest.

1. A magnetic needle, suspended by a vertical thread and deflected 53° from the magnetic meridian, returns to it by a series of oscillations, gradually diminishing. If we note the number of oscillations that take place before it is reduced to an arc of 43°, we shall find that the number varies with the nature of the substance above which the needle oscillates.

The results furnished by the metals, especially by copper, are very remarkable. A plate of this metal was found to reduce to four the number of appreciable oscillations of a needle, which in the

air, and without the influence of copper, made more than 400 oscillations.

It is well ascertained by experiment, that a magnetic needle experiences from all bodies, and especially from metals, an influence which diminishes rapidly the extent of the oscillations without altering their duration.

2. M. Arago, guided by a principle in mechanics, that action and reaction are equal, succeeded in drawing a needle at rest by a plate in motion.

The apparatus employed in these new experiments is composed of two parts, separated from each other; the first consists of a kind of clock-work, all the wheels of which are of copper, which communicates to a plate a motion of rotation, regulated by a fly, the velocity of which is measured by a hand, that points out the number of revolutions performed in a given time. The second part consists of a glass cylinder, closed at the lower end by a sheet of paper and at the upper by a glass plate, at the centre of which is fixed a copper rod, which is raised or depressed at pleasure, and which carries the thread to which is suspended a magnetic needle. An index shows the direction of the needle, the centre of which is made to coincide with the centre of the turning plate.

A moderate velocity of rotation, impressed upon the metallic plate, causes the needle to deviate in a remarkable manner. If the motion is gentle and uniform, the needle fixes itself in a determinate position; if the motion is rapid enough to produce a deviation of more than a right angle, the needle is drawn on and made to describe an entire circumference, continuing its motion with a velocity that goes on increasing till the plate ceases to turn. To give an idea of the intensity of the force under consideration, we will state the following result.

A plate of copper about a twelfth of an inch thick, moving with a velocity of four or five revolutions in a second, impressed, at the distance of more than an inch, a motion of rotation upon a magnetic bar, the length of which was a little less than the diameter of the revolving disc.

M. Arago, wishing to have a datum upon the magnetic power of copper destitute of motion, subjected a needle to the action of a bar of this metal, and observed, at the distance of $\frac{4}{1000}$ of an inch, an angular displacement of above 2′.

All the metals are capable of producing similar phenomena, but to a much less degree than copper. If we substitute for the plate the same metal, reduced to powder or shavings, the needle is scarcely affected.

This new force diminishes with the distance, and it is inferred from the phenomena of rotation, that it acts perpendicularly to the radii of the disc and parallel to its surface.

The following experiment shows, that there exists also a repulsive force perpendicular to the surface of the disc. If we suspend vertically a magnetic needle by one of its extremities to the end of a scale-beam and balance it, upon making a copper disc revolve below the needle, it is repelled, since the other end of the balance preponderates.

M. Arago has further proved, that there exists a force acting in the direction of the radii and parallel to the surface of the plate. For, if we render vertical a dipping needle, and cause the plane of its motion to pass through the centre of the plate, upon bringing the point of the needle above the different points of the same radius or its prolongation, it will be seen that it is repelled, when it falls without the plate.

This repulsive force diminishes in proportion as we approach the centre, till it becomes nothing at a point nearer the edge than the centre, after which it changes to an attractive force; finally, it is reduced to nothing at the centre.

Thus the action of a circular, horizontal, metallic plate, turning on its centre, may be decomposed into three forces; one perpendicular to the plate, another horizontal and perpendicular to a vertical plane, passing through the radius that terminates at the projection of the pole of the needle, and a third directed parallel to the same radius.

M. Arago sought the relation of these three forces, and found that it varies with the velocity of the rotation of the plate. The importance of these new facts is so much the greater as the connexion with former facts is less known.

If we make narrow slits in the disc, at a small distance from the centre, there is very little deviation produced.

These curious experiments of M. Arago have been repeated and confirmed by other philosophers. Herschell and Babbage have

moreover remarked, that, by filling up the slits made in the disc by a metal, the magnetic influence of which is much inferior, we restore to the platé apparently all its energy; but, if we make use of a powder or a liquid in closing the slits, we do not repair the loss of intensity occasioned by the interruption of continuity.

The same philosophers have represented by the following numbers the powers of different metals. Copper 1; zinc 0, 93; tin 0, 46; lead 0, 25; antimony 0, 09; bismuth 0, 02. They have also determined, that a screen of any substance, excepting iron, nickel, cobalt, manganese, exerts no influence when it is placed between the magnet and the revolving plate, and that a turning plate does not draw after it another plate, left at rest.

Professor Barlow has observed, that motion increases the magnetic power of iron.

M. Ampère put in motion by the action of a revolving disc a voltaic conductor, arranged in the form of a spiral at each of its extremities.

A short time only before the discovery of Faraday, Despretz wrote thus: "The theory of the influence of revolving plates is not yet perfected. It has been supposed, that each pole of the needle gives rise to a pole of a contrary name, which is displaced in the surface of the plate, and which disappears less rapidly than it is formed. But the consequences of this hypothesis are not in exact accordance with facts, especially that relating to the experiment with the balance."

238. It appears, then, that as there are two ways of charging a conducting substance with statical electricity, viz. conduction and induction, so also there are two similar processes for obtaining electricity in motion; and the two cases are so far analogous that the induced electricity is in one case opposite in kind, and in the other in direction, to the primitive electricity. In the latter instance, however, the effect is momentary and only takes place when the connexion with the battery is made and broken. It appears, farther, that currents are likewise induced in a copper wire by winding it round a piece of soft iron which alternately receives and loses its magnetism by the influence of a steel magnet. These secondary currents, whether proceeding from a primitive current simply, or from a primitive current surrounding a bar of soft iron, or from the

action of a magnet upon a bar of soft iron enclosed in the second coil, resemble in all essential circumstances common voltaic electricity, and will produce all the chemical and physiological effects of which the latter is capable under the same state of quantity and intensity. It becomes an object, therefore, to contrive some way of making and breaking contact with such rapidity that the induced current shall furnish a constant supply of electricity.

The first instrument we shall describe, as adapted to this purpose, may be called an electro-magnetic machine, as the current is induced by an electro-magnet. Let *A* represent a compound coil Fig. 166. around a bundle of wires of soft iron or a bar, the ends of which may be seen projecting at *a*: *b*, *b'*, are two brass straps, confining the magnet to the base-board; *C* and *Z* are the battery connexions for the interior coil, which consists of large wires, firmly soldered at their extremities to the bottom of these cups:—the wires from the battery are attached to the cups by means of binding screws; *dd* are the terminations of the exterior coil, which is of fine wire, and may be 2000 or 3000 feet in length. The movable part of the apparatus, *e*, *f*, *g*, *h*, is for breaking the battery connexion, and is called the electrotome; *c* is a stout copper wire passing through the shaft *k*: one extremity of this wire dips into the mercury cup *m*, the top of which is made of glass, and the brass base of which is soldered to the brass strap *b'*. At the other extremity of *e* is a small ball of iron *g*, which will be attracted by the soft iron *a*, when the current is flowing from the battery through the inner coil: *h* is a short piece of wire soldered to *e*, and descending into the mercury cup *n*, which is soldered to the brass strap *b*. The brass ball *f* is movable on the projecting screw *o*, and serves as a regulator to the vibrations of the electrotome. The course of the circuit from the battery through the interior coil is as follows: from the cup *c* by the dotted line to the brass strap *b'*, thence through *m c h n b*, to one end of the large wires: the other ends are soldered to the cup *c'*. When *e* dips into the mercury at *m*, the circuit is completed: the magnet attracts the ball *g*, and raises *e* from *m*, producing a bright spark from *m*, and a powerful shock from *d*, *d*; the former arising from the secondary current, induced in the battery circuit when it is broken, and the latter caused by the secondary current induced at the same time in the surrounding coil of fine wire. The

current from the battery ceasing, *e* drops by its own weight, re-establishes the connexion, and thus a very rapid vibration is sustained. The extremities of *h* and *m* should be covered with solder, in order to have a good metallic connexion for the current.

It is important to have some apparatus for showing the current, which one wire induces in another wire independently of any ferru-
Fig. 167. ginous substance. Let *a a* be a double helix, similar to that used in the preceding instrument, without the soft iron bar; so as to form a hollow cylinder. The current cannot here be cut off by the periodic attraction of the electro-magnet. We therefore make use of some mechanical means not connected with the current. The inner helix, which is composed of five strands of large insulated copper wire, amounting to 100 feet in length, is connected at one termination to the cup *c*, while the other extremities are soldered to the middle brass band *e*, at the top of which is a cup containing mercury. Into this cup dips a copper wire *o*, connected above with the bent wire *e e'*, which by means of an escapement, impelled by a spring wound up at the milled head *f*, vibrates rapidly and dips successively into the cups of mercury *m m'*. These cups are soldered to the brass bands at the ends of the helix. These bands are joined by wires underneath the base to a cup *Z*, corresponding to *C*. Suppose now that the wires from the electromotor are confined by binding screws in the cups *C* and *Z*, and the milled head is wound up so that the arms *e e'* may vibrate rapidly, the circuit for the current is complete whenever either arm dips into its corresponding cup. But during the passage from one contact to the other, the circuit is broken. The circuit is made and broken once during every vibration of *e e'*. A rapid succession of secondary currents will be induced in both helixes; that in the inner helix shows itself by the sparks in the cups *m m'*. If the ends of the exterior helix are fixed to *b b'*, and wires with handles are bound there, a shock will be felt on grasping the handles, especially if the hands be moistened in some saline solution. A variety of curious experiments of analysis may be tried with this apparatus.

For instance, if a bar of soft iron be introduced into the cylinder, the secondary currents are very much increased, as is shewn by the increased brilliancy of the sparks and the greater severity of the shocks. If a bundle of fine wires be introduced instead of a solid

bar, the effect is still more increased. This may be owing to the mutual action of the contiguous ends of the wires in neutralizing one another's magnetism, when the current ceases to flow. If the ends of the outer helix are connected together when the arm is vibrating, the sparks shew that the secondary current in the inner helix has very much diminished. To understand this, we must consider, that the secondary current flowing at that moment in the outer helix, tends to produce a tertiary current in the inner helix, which is opposite of course to that induced by the interruption of the battery current; and hence in part countervails the effect of the latter, as seen by the diminished spark. If the bar or bundle of wires, before being introduced, be surrounded with a tube of brass, the shock and spark are exceedingly reduced; and this too may be explained in the same way, the brass tube acting as another closed circuit. For if a slit lengthwise be made in the tube, this influence is not perceived: or if glass, or some other non-conductor of currents be used instead of the brass tube, the reduction does not take place in the secondary current. It is felt that the *surface* of a bar of soft iron may act in the same way; since if we take out a section to the axis, the electro-magnetic induction is increased. Perhaps this is another reason why the bundle of wires succeed better than the bar. An iron tube also produces a greater effect than a solid bar of the same diameter. In all these experiments, the result will bear some proportion to the size of the battery that is used: though on account of the mechanical contrivance which acts as an electrotome, a very feeble current, such as would be produced by a single voltaic element of small size, would have a very perceptible influence.

To prove the similarity or the identity, of the current produced by voltaic or electro-magnetic induction to the direct battery current, it is only necessary to show that the effects produced by each are the same. We have already seen that the secondary current is accompanied with a shock and a spark. It can also be proved to have the decomposing power of the primitive current. For this purpose, it is only necessary to make use of an instrument similar to that used and described before, in the decomposition of water. As the direction of the momentary induced currents alternate at every making and breaking of the contact, instead of two glass tubes, one Fig. 161

over each wire, a single glass tube large enough to cover both wires is substituted, it being impossible to collect the gases in separate tubes unless the current induced at making or breaking is used instead of both of them. The apparatus before described makes no provision for shutting off the alternate induced currents, so that here when we connect the cups which lead to the ends of the outer helix with the wires of Fig. 168, both gases must be collected in one vessel. For the success of this experiment it is necessary that the extremities of the platinum wires should be guarded by glass or sealing wax. When the experiment is performed in a dark room, whilst the decomposition of the water is in process, one of them appears touched with a steady and brilliant light, whilst the other emits a faint and intermittent one. Also a very acute ticking sound is noticed, as often as the battery connexion is broken. Wire also may be scintillated by the same secondary current, and a Leyden jar can be feebly charged.

239. We shall mention one other piece of apparatus for producing a constant succession of induced currents. In many respects it is similar to the last two, though it differs from them, as they differ from each other, in the electrotome contrivance. The double helixes are placed in an upright position, and one is entirely independent of the other, so that it can be readily slipped on and drawn off. This is convenient in analyzing the process of voltaic induction, as we can bring one helix to the side of the other, insert it to a greater or less extent, and examine the difference produced by
Fig. 169. these various positions. *RR′* is a rasp to one end of which the cup *B* is soldered. One termination of the coarse inner helix is at *Z*, the other at *B*, so that if one wire from the battery is bound to *Z*, and the other is drawn over the rasp, the battery contact will be rapidly made and broken, and the secondary current will exhibit itself by brilliant scintillations on the rasp, or by a shock at the handles which are connected with the exterior helix. On the same stand is the revolving armature, already described; one end of this electro-magnetic coil is attached to the cup *C*, the other to the cup *Z*. Now if *C* and *Z* be connected with an electromotor, the current in one position of the armature will pass from *C* through the electro-magnetic coil to *B*, thence through the inner helix of the cylinder to *Z*, and thence to the other end of the battery. We see then

how by the revolution of the armature the battery current in the inner helix will be very rapidly interrupted. By inserting a bar or a bundle of wires into the inner helix, the same experiments may be tried as with the other compound helixes and electrotomes.

With all these instruments, whenever the shock is received from the secondary current, it is felt more acutely in one arm than in the other; and by shifting the handles, the place of this superior shock will also change from one arm to the other. At first view, it does not seem as if it could depend on the direction of the current, because the initial and terminal induced currents are opposite. But there is no difficulty here when it is considered that it is only the terminal induced current that produces any considerable physiological effect, and hence it is found that the arm connected with the negative cup experiences the greatest convulsions. Before the discovery of induced currents, it had been observed by Prof. Marianini that a similar difference was exhibited when the shock was taken directly from a battery, with a large number of pairs of plates. This difference not only betrays itself in the sensation, but to the eye in the degree of muscular contraction, and is attributed by the Italian philosopher to the principle that the greatest effect on the muscles is produced by the voltaic current when it travels in the direction of the ramification of the nerves.

240. As there is a magnetic property induced in magnetic substances by the induction of a current, so we have also seen that there is a current induced in a wire by a common magnet. Like all the other instances of induced currents, the secondary current is intermittent, flowing only at the moment when the magnetism is imparted to a soft iron bar, or destroyed in it.

Machines have also been contrived for producing a rapid succession of these secondary currents, so as to make them a permanent and abundant source of electricity. The most convenient on the whole is that made by Clarke, which consists of an upright, compound, horse-shoe magnet, pressed against a board, *D*, by the cross-piece *C*. By means of a multiplying wheel, *E*, the armature *ABFG* is made to revolve rapidly before the poles of the fixed magnet. This armature consists of two pieces of soft iron, connected at right angles to the piece of iron *AB* by screws; round the legs or branches Fig. 170.

of this are wound about 1500 yards of fine, *insulated* copper wire; one end of which is connected to a collar of brass, against which the spring *H* presses, the other end being soldered to an insulated brass collar, *I*, part of whose circumference has been removed, as shown on a larger scale in the side figure. A thick copper wire, *K*, presses against *I*, and is connected by a brass pillar, *P*, with a metallic strap, *L*, fixed on one side of the wooden block *N*, whilst a similar piece of metal, *M*, with which it is connected by a bent wire, *T*, is on the opposite side, and supports the spring *H*. When *FG*, and consequently their iron axes, are opposite to the poles of the magnet, the latter, by induction, converts the inclosed iron into a temporary magnet; at the instant this action occurs, the electric equilibrium of the wire wound round it becomes disturbed, and a current of electricity rushes through the coil. If the armature be turned half round, the magnetism of the iron piece becomes reversed, and a second current in an *opposite* direction is excited; and as at the moment this takes place, the wire *K* comes in contact with the interrupted portion of the collar *I*, a bright spark passes between them. On revolving the armature with rapidity, a succession of vivid sparks ensue; and if wires fixed to the brass pieces *LM* be immersed in acidulated water, decomposition of that fluid will occur, the oxygen and hydrogen gases being evolved alternately from each wire; as of every two induced currents, one is always in the opposite direction to the other, the alternate ones only moving in the same direction.

If a copper cylinder be grasped in each hand, whilst wires connected with them communicate, one with the strap *L*, and the other with a cavity excavated in the end of the revolving armature, on turning the wheel *E*, a rapid succession of currents is sent through the body of the person grasping the cylinders, producing a series of severe and almost intolerable shocks, the muscles becoming so firmly contracted that he is generally unable to drop the conductors. If the wires, instead of terminating in copper cylinders, be furnished with platina points, electrolytic decomposition of any conducting fluid they are immersed in will ensue.

241. If an armature, having a *short* helix of thick, insulated copper wire, be substituted for the armature *AB*, the intensity of the evolved electric currents will be diminished, and no shock or chem-

ical action will result from them. The vividity of the spark at *I* will be, however, increased, and pieces of platina wire readily ignited by allowing the electricity to pass through them. The ordinary phenomena of electro-magnetic rotation may be produced by passing these currents from the short helix through the appropriate pieces of the apparatus.

242. A very simple and ready mode of exhibiting the electro-magnetic spark, as it is termed, by the induction of a permanent magnet, is to wind round a piece of soft iron, *AB*, about ten yards Fig. 172.
of thick insulated copper wire or ribbon. Let one end of this coil be soldered to a plate of amalgamated copper, *C*, upon which the other end, sharply pointed, is made to press with elasticity; to effect which, it is bent into an elliptical form, *DE*. On placing this armature on the poles of a strong magnet, *NS*, the bar *AB* becomes magnetic by induction; and on suddenly *jerking off* one end, as *B*, from the pole *S*, the bar nearly loses all its polarity, and the electric current developed is shown by a vivid spark occurring at the point where *E* presses on *C*, as it becomes slightly raised from the plate by the sudden motion communicated to *AB*.

243. As in these cases the electricity evolved bears a ratio to the magnetism induced in the iron nucleus of the armatures, it follows, that by increasing the intensity of this magnetism, the electric current becomes proportionably increased in tension and quantity. Since by means of a current of electricity of low tension we can excite powerful magnetism in an iron bar, the application of this as the inducing agent has been used in the construction of these machines; indeed, it was by a contrivance of this kind, that Faraday first discovered the existence of these currents. The double helix and electrotome, already described, may be regarded as magneto-electric machines, in which an electro-magnet is used instead of an ordinary magnet.

244. A more convenient form of the magneto-electric machine is exhibited on the next figure, where *NS* represents the magnet, Fig. 173.
which is placed horizontally; *AB* the soft iron revolving armature with the coils attached. The axis carries with it two cylindrical pieces, insulated from it and from one another, and which are pressed in succession by the springs, *DE*, which connect, by wires running under the base-board with the binding-screws, *C* and *Z*. One

end of each of the coils is attached to one of these pieces, and the other end to the opposite piece. The break between the two pieces must be so placed that the springs may shift from one half to the other, at the moment when the current in the coils changes its direction by passing from one pole to the other of the magnet. When this is done, we are sure that the opposite currents alternately flowing in the coils will always run in the same direction from *C* to *Z*. This is what is called the primitive magneto-electric current; which by the pole-changing arrangement just described, and which is represented at large on the 162 figure, flows constantly in the same direction whenever the circuit is completed from *C* to *Z*. This contrivance of Dr. Page gives his machine great advantage over all others. With that of Fig. 170, we obtain a current in the same direction by using the single break piece of Fig. 171; but in this case we do not change the direction of the currents, but use only every alternate one; which amounts to the loss of half the electricity developed. In order to get the secondary current from the machine last described, we have one end of the wires connected with the axis *A*, and the other with the spring *R*, which acts upon the teeth of *W*. Every time that the spring, by the revolution of the wheel, *M*, touches one of these teeth, the circuit is closed and broken, and according to the general law of induced currents, a secondary current flows through the coil and appears at *C* and *Z*. This secondary current becomes visible in the spark which appears at the break-piece. Now, in some experiments, the secondary current is preferable, while, in others, the primitive current will produce the greatest effect. For example, we remove the break piece and connect *C* and *Z* with the apparatus for the decomposition of water, and we can collect the two gases separately or together; the decomposition having been effected by the primitive current. We connect the mercury vessels *A* and *B* of Fig. 144, with the binding screws *C* and *Z*, and the wire-frames will rotate from the action of the magnet on the magneto-electric current which is passing through them, as they did before when voltaic electricity was sent through them. The magnetic properties of the electro-magnetic current are again shown by the following experiment, with the secondary current. We apply the spring against the break, and then bind to *C*
Fig. 171. and *Z* the ends of a coil, wound round a bent piece of soft iron, *A*;

as soon as the machine is turned, the iron becomes magnetic and attracts the keeper, *B*. If we now make use again of the primitive current, and connect to *C* and *Z* two pieces of copper wire, twisted together at *A*, and then bring the free extremities within an inch of one another; if a piece of fine platina wire is soldered to these ends and the magneto-electric current sent through it, the platina wire will be ignited so as to inflame ether, gunpowder, &c. If we wish to obtain the shock from the magneto-electric machine, we apply the break-piece, and grasp in the hands, moistened or otherwise, two metallic bundles which are connected by short wires with *C* and *Z*, and the secondary currents will be sent through the body, producing great contraction of the muscles. Fig. 175.

Theory of the Electro-Dynamical Forces, including a new Theory of Magnetism.

245. We have given in detail all the experiments which show the directive, the attractive, and the repulsive forces mutually exhibited between magnets and currents; we have shown the tangential character of the directive forces, and the various revolutions to which they conduct, in the system of bodies; we have illustrated the inductive power of electricity in producing magnetism, or electro-magnetism; the inductive power of magnetism in generating currents or magneto-electricity; and the inductive power of currents in producing currents, or voltaic induction. Every experiment on the subject points to the most intimate relations between electricity and magnetism. We are now prepared to look at the theory which declares them to be identical; which may be regarded as being at the same time a theory of the electro-dynamical forces and a new theory of magnetism; which indeed by a new step of generalization merges the facts of both sciences under a few common principles. Accordingly, this new theory of magnetism supposes that magnetism does not exist as an independent fluid, but that polarity results from currents of electricity running at right angles to the length of the bar; the magnetic fluid is therefore the same thing as the electric fluid. If this idea of Ampère, that magnetism is derivable from currents at right angles to the line which connects the poles of the

magnet be correct, it follows, that currents flowing in that way ought to possess polarity. Now we have already seen that a helix, through which a current is passing, directs itself under the action of the earth as a magnet would do; that it exhibits all the other forces of the common magnet, and that its poles may be changed by altering the direction of the current. The experiments on voltaic induction show that a current possesses the power of inducing parallel currents in other bodies out of its own circuit; therefore, we have no difficulty in explaining whence the soft iron in the electro-magnet derives its great and sudden accession of magnetism, and why its poles change when the current of surrounding coil flows in an opposite direction. It is not essential, however, for an explanation of the facts to suppose that the voltaic current has induced in the soft iron corresponding currents which did not exist there before. It will answer as well if we suppose that in soft iron, there are always numerous currents of this kind flowing in every direction, and that the presence of the current in the coil exercises, according to the well known action of a current on a current to which we shall presently recur, a directive power over them so as to bring them all into one common direction and parallel to itself. Why these currents exist in greater abundance or under greater freedom of motion, or why according to the other idea they are more abundantly induced in soft iron than other kinds of matter, is a difficulty not peculiar to the new theory of magnets, but felt by it in common with the ordinary ways of explaining the magnetic phenomena. A difference of structure, which we call the coercive force, will explain this distinction as intelligibly upon one hypothesis as upon the other. Again, if Ampère's theory be correct, it follows that the polarity of common steel magnets proceeds from the currents of electricity which are flowing in a determinate direction — with this difference merely, that while in electro-magnets the currents are induced by an artificial current, in the ordinary process of magnetizing, they are induced by the natural currents which constitute the magnetic state of the bar with which the new magnet is touched. These currents, moreover, if they exist in steel magnets, ought to possess the inductive power of other currents, in reproducing themselves; and all this is known to be a fact from the phenomena of magneto-electricity,

which is the name given to a current when it is induced by a steel magnet. Every thing concurs to show that the magnetism of the earth is the same thing as passes by that name in smaller bodies, so that the theory we are now considering would naturally resolve all the phenomena of Terrestrial Magnetism into the action of currents, running parallel to the magnetic equator. The source of these currents may be found in various quarters; in volcanos, in the voltaic action that must be constantly going on in the bowels of the planet; in the influence of the sun's rays, developing thermo-electricity on the earth. These currents, whatever be their origin, will close their circuit by the best conductors, and as the great metallic ranges run nearly east and west, the magnetic poles approximate to the geographical poles. It is no small confirmation of this view of the earth's magnetism, that such currents have been found by direct experiment upon them to have a physical existence. Finally, when we come to refer the phenomena of terrestrial magnetism to voltaic and thermo-electric currents, we are at no loss to account for the derangements in the magnetic elements, whether we consider the daily and yearly oscillations which seem to have a regular period, or the larger and irregular bounds which are sometimes made by the instruments which indicate the changes of those elements. If we take Fig. 176. a small globe and wind its equatorial parts with a few coils of fine insulated copper wire, and then send a current through them, we may bring a horizontal and dipping-needle to various parts of it, and show changes of position corresponding to those which the same instruments indicate in similar situations on the planet. This is a great subject; but it has just been opened, and we should expect that much speculation must be mixed with what is a clear induction from the facts and the experiments. But these experiments and facts suggest the idea, that the motion of the earth on its axis and in space may excite secondary currents similar to those shown in our lecture rooms, and which, operating on a grand scale, modify the intensity, if they do not constitute the basis, of Terrestrial Magnetism.

The new theory of polarity, which we have briefly elucidated, leads to a new view of the electro-dynamical forces. The problem for investigating the mutual action of magnets and conductors is reduced to the determination of the forces exerted between currents differently disposed in regard to one another. French writers on

Electro-Dynamics have given particular attention to this point, and have illustrated this part of the subject by a large variety of experiments. These experiments would possess less interest than those presented above to the general student, on account of the powers of analysis which they would require; and therefore they are omitted for the most part in an elementary treatise, having a more popular object than a complete, scientific examination of the subject. There are some general results and experiments, however, that must not be omitted even here, and which we now propose briefly to recapitulate.

Attraction and Repulsion of Electrical Currents.

246. Soon after the discovery of Oersted, it was found by Ampère, that *two electrical currents attract one another when they are parallel and running the same way, and that they repel one another when they are parallel and running opposite ways.* He afterwards generalized the subject still further, and announced it in the following propositions. *There is always an attraction when the two currents proceed in such a manner as to approach both toward, or to recede both from, the vertex of the angle formed by*
Fig. 177. *the two wires; and repulsion in the opposite case, in which, while*
Fig. 178. *one approaches, the other recedes from the same vertex.*

Moreover, in order to give to the law above stated still greater generality, it may be remarked, that *where the conducting wires are not in the same plane, we may consider as the vertex of the angle formed by the wires the line which measures the shortest distance between them.*

If the two conducting wires are parallel, they are to be regarded as making an infinitely small angle with each other, the vertex of which is at an infinite distance.

The repulsion in all these cases is equal to the attraction, as may be shown by the following experiment.

Fig. 179. A conducting wire, bent back upon itself in such a manner that the two portions *AB*, *BC*, shall be separated from each other only by the silk with which they are covered, has no action upon another wire *DE*.

The action of a rectilinear current is the same as that of a sinuous current which deviates but little from a straight line; as may be shown by substituting, in the preceding experiment, the sinuous wire for the rectilineal wire *BC*. Fig. 180.

247. Two contiguous portions of the same rectilinear current may be considered as two currents forming with each other an angle of 180°, the vertex of which is at the point which separates them. It will hence be seen, that, the current of one of the portions proceeding toward the vertex, and that of the other receding from it, there ought to be a repulsion, as M. Ampère has found by the following experiment. Upon the dish *ABCD*, separated by the insulating Fig. 181. partition *AC* into two portions of the same size, and filled each with mercury, we place a copper wire covered with silk, the two branches *q r*, *p n*, being made to float upon the mercury parallel to the partition, while the uncovered extremities *r s*, *n m*, touch the surface of the mercury. Putting now the end of the vitreous wire in the cup *E*, and that of the resinous wire in the cup *F*, or the reverse, we establish two currents independent of each other, each of which has for a conductor a portion of the mercury and a portion that is solid. Whatever be the direction of the current, it will be seen, that the two wires *q r*, *p n*, move off parallel to the partition *AC*, in the direction opposite to that in which the instrument is in communication with the voltaic apparatus, which indicates a repulsion for each wire between the portion of the current established in the mercury and its prolongation in the wire itself. The motion of the wire is more or less easily effected according to the direction of the current, since, in the one case, the action of the earth upon the horizontal portion *q p* concurs with the repulsion in question, and, in the other, it is opposed to it.

It will be observed that the attractions and repulsions, here spoken of, differ in the form at least in which they may be announced from those of statical electricity.

In ordinary electrical attractions and repulsions, it will be remembered that it is bodies oppositely electrified that attract, and similarly electrified that repel one another. We have to notice farther, that in statical electricity, repulsion follows attraction more or less quickly, whereas here the attraction remains so long as the currents continue to flow. Moreover, the forces exerted between

currents are independent of the pressure of the air which retains ordinary electricity on the surface of conducting bodies. A very simple form of apparatus will show the attractions and repulsions of
Fig. 182. currents. Let *AB* be one wire suspended freely and connected with the cups *AB*, and let *CD* be another wire suspended in the same way in connexion with the corresponding cups. By alternately connecting the cups at the same end of the apparatus with the same, and with opposite poles of the electromotor, the attractions and repulsions will be clearly exhibited. The apparatus is made more delicate by extending upward the vertical parts of the wire frames and placing at the ends balls whose weight shall balance that of the wire below the points of suspension.

248. *If a current rectilinear and indefinite in both directions, act upon a movable current, placed perpendicularly to it, and having one of its extremities near it, the former will carry the latter parallel to its position, and the motion will take place in the direction of the indefinite current, when the movable current recedes from it, and in the opposite direction when the movable current approaches it.* This will be rendered evident by a slight
Fig. 183. inspection of figures 183, 184. For if we take, upon the current *MN*, from the point *o*, where it approaches nearest to the movable current, two equal distances *o m*, *o n*, and from any point *c* of the movable current draw two oblique lines *c m*, *c n*, they will be equal, and will make equal angles with the directions of the two currents; whence it follows, that the two small portions of the indefinite current, situated at the points, *m* and *n*, act with the same intensity upon the small portion situated in *c*. But, of the two equal forces *c p*, *c q*, produced by these two small portions, the one is attractive and the other repulsive; hence, by forming a parallelogram upon their directions, this parallelogram will have for its diagonal the line *c R* which is the resultant of the two actions, and evidently parallel to *MN*. The resultants of the actions exerted upon the other points of the movable current being also parallel to *MN*, it will be the same with the total resultant. Now, from what we have just said respecting the mutual action of two currents, it will be seen, that the action between *m* and *c* is repulsive, and that between *n* and *c* attractive. Whence it follows, that the movable current is carried in the direction *c R*, which is that of the indefinite current *MN*. The reverse takes place in Fig. 184.

The action of these two currents is necessarily reciprocal, so that, if the conductor *MN* be the movable one, and if it could slide along the straight line *MN*, it would proceed from *n* toward *m* in Fig. 183, and take the contrary direction in Fig. 184. This is not easily verified with a rectilinear current, but, by substituting a circular current, we may readily obtain a similar result.

This experiment is due to M. Savary. A circle of copper, interrupted in *A* by a small piece of ivory *CA*, is immersed in an acid solution, contained in a metallic vessel that communicates with one of the extremities of the voltaic apparatus, the other extremity communicating with a small cup of mercury, in which terminates the point *p* that supports the circle, and which is united to this circle by the radius *OC*; another radius *OE* helps to support the circle, but is of an insulating substance. It will be seen, that the instrument turns constantly in the direction *AEC*, whatever be the direction of the current which traverses it. Suppose, in the first place, that the current comes by the centre, it will reach the point *C* by the radius *OC*, follow the copper circle *CEA*, traverse the acid solution by the lines *l m n*, *l' m' n'*, &c., perpendicular to the circle, and arrive at the metallic vessel. The whole current does not immediately pass into the acid solution; on account of the obstacle which exists in the contact of two bodies, and on account of the feebleness of the conducting power of the liquid compared with the conducting power of the metal. Take a point *l* upon the circle. In the angle *m l h* there is a repulsion between the water and the circle; but in the angle *m l k* an attraction takes place. The attraction and repulsion concur to give to the circle a motion in the direction *k h* or *AEC*, and to the water a motion in the opposite direction. This last motion is insensible on account of the liquid mass which is so considerable. If, on the other hand, the positive pole communicates with the external vessel, then the electrical current would reach the circle perpendicularly, according to the directions *n m l*, *n' m' l'*, &c., and would take the course *AECO* to arrive at the cup. Repulsion always taking place in the direction *m h*, *m' h'*, the circle would turn in the same manner as before. It may be remarked, that, in the first case, *AEC* is opposite to the current in the movable conductor, and in the second case it is in the direction of the current. We can only change the direction of the rotation, by substituting for the Fig. 185.

above circle another circle, represented in Fig. 182, in which the insulating part *AC* is changed to the other side of the conductor *OC*.

249. If the movable current traverse the indefinite current by extending itself equally on both sides, the direction of the movable current will be such as to approach it in the half *BA*, and to recede
Fig. 186. from it in the half *AC*; the first will be carried in the direction *BE*, opposite to that of the indefinite current, and the other half *AC* in the direction *CF*, which is that of the indefinite current. We have, therefore, a couple, composed of two forces *BC*, *CF*, which would no longer produce a motion of translation, but would cause the movable current *BC* to turn about the point *A* until it became parallel to *MN*, and directed the same way. It may be remarked, that in this experiment, as in all those in which the movable conductor does not strike against the fixed conductor, the motion, on account of the velocity acquired, takes place beyond the position of equilibrium and then back again in a series of oscillations.

Fig. 187. 250. Let us suppose now an indefinite current *MN*, and a current *BA* in a conducting wire, movable about one of its extremities *A*, so that it can describe about the point *A* a circumference; when the current comes from the circumference to the centre, that is, in the direction *BA*, and is in the situation marked *BA* in the figure, it will recede from *MN*, and will consequently be carried in the direction of the current *MN*, which will bring it into the position *B'A*. It will then be parallel to *MN*, and have the reverse direction; consequently it will be repelled and take the position *B''A*. Then, as it approaches the current *MN*, it will be carried in a direction opposite to this last, and will take the position *B'''A*; being now parallel to *MN*, and directed the same way, it will be attracted, and will take the position *BA*, whence the same motion of rotation will continue indefinitely.

So long as the current *MN* is near the point *A*, the action exerted by this movable current upon the wire, goes on diminishing from the position *BA* to the position *B''A*, since the distance between the two wires increases; but, if the current *MN* were very far from *A*, the difference in the distance would become insensible, and then the calculus shows, that the action of *MN*, in turning *AB* about *A*, is the same in all the positions which the movable conductor successively takes. The action may be rendered uniform,

even for a small distance, by bending the fixed conductor in such a manner as to form a circle about *A*; for it is then clear, that its action in turning *AB* about the point *A* becomes constant.

In this experiment we make use of a metallic vessel *DEF*, about an inch and a half in depth, in the bottom of which, at the centre, is inserted a small hollow cylinder *d e f*, of the same height. The vessel *DEF* is filled with a weak acid solution. We introduce into the opening *d e f* a cork stopper, through which passes firmly a large copper wire *PH*, fitted to raise or depress the cup *H*, in which rests the point *s* of the movable conductor *s k p*, connected at *p* with a copper circle *p l*, the support *l k* being of some non-conducting substance. The wire *PH* communicates at *P* with one of the extremities of the voltaic apparatus, for example, with the vitreous. To the vessel *DEF* we solder another wire *MRTUN*, which makes several turns about *DEF* for the purpose of increasing its energy; it then returns to *U*, near the first wire, and thence passes to the other extremity of the voltaic apparatus. When the communication is established, the current mounts through the wire *PH*, descends by the movable conductor, traverses the liquid, passes through the wire *MRTUN*, and produces a continued motion, in the direction *v z*, of the radius *k p* of the movable conductor. If both branches, *k l*, *k p*, were conductors, the velocity of rotation would be doubled. Fig. 188.

The currents which traverse the liquid have no influence upon the rotation; for, if only the branch *k p* were a conductor, the current *p x l* would be in a direction the reverse of that of *p y l*. If both the branches *k l*, *k p*, were conductors, there would be in the two semicircles two opposite currents. Thus the actions produced by the currents of the liquid destroy each other.

251. We have seen that where separate conductors, free to move, are carrying currents of electricity, they tend to arrange themselves parallel to one another. If while they are moving forward to this position, the direction of one of the currents changes by means of the pole-changer, a new impulse will be given to the motion, and Fig. 189. in this way a continued rotation of one coil within another will be produced. One coil will act therefore upon another coil, as we have before seen that a single coil will act upon a magnet, or the magnet upon the coil; and this we should expect, if magnetism be

reducible to currents flowing at right angles to the axis of magnetism. We shall not fail to notice that in the earliest experiment of the deflection of the needle so as to stand at right angles to the direction of the current, this tendency to parallelism was manifested; since when the magnet is at right angles to the conductor, the currents of the magnet, which run at right angles to its length, become parallel to the voltaic current. The attractions and repulsions of currents, according to their relative directions, is clearly demonstrated by experiment, and the law of this force, as it is exerted between the elements of the conductors, may be deduced by calculations from the complex phenomena of indefinite currents acting one upon another. Calculating according to the same formula, as it has been obtained by Ampère, the action of two helixes upon each other, or of one helix upon a conducting wire, we reach the same laws as were deduced experimentally by Coulomb for the mutual action of two magnets, and by Biot and Savart for the force which a magnet and the element of a conducting wire exert upon each other. Besides the general confirmation which the new electro-dynamical theory receives from facts and experiments, it has successfully passed, so far as the investigation has been pursued, that severe trial which judges the validity of all physical theories; a numerical comparison, that is, of its fundamental principles, when developed into their minute mathematical details, with the results of observation and experiment.

Sustaining Batteries.

252. In the preceding experiments, upon the mutual action of currents and magnets, and the influence of currents upon one another, a very strong battery is not required. But it is important that the action of the battery should remain nearly uniform for several hours. Hence the contrivance of sustaining batteries, as they have been called. That of Mr. Sturgeon is very simple. It consists simply
Fig. 190. of a double copper cylinder, into which a single cylinder of zinc may be placed: a solution of sulphate of copper is poured into the double copper cylinder, and the zinc and copper cylinders being connected by a wire, a current will flow and continue for a considerable time. In Mullins' sustaining battery, the action is still more

feeble, and continues of course a proportionally longer time. The copper cylinder, which is here the inclosed cylinder and single, is covered with a membranous substance; a solution of sulphate of copper is poured between the membrane and the copper; a solution of common salt is put between the membrane and the outside zinc; the voltaic action will then go on very slowly through the pores of the membrane. A sustaining battery of this kind will retain its power for weeks. Daniell's sustaining battery differs slightly from that of Mullins. The outside cylinder is copper, and a small rod of zinc is run into the hollow centre. A membrane separates the copper from the zinc. A solution of sulphate of copper is poured between the copper and the membrane, and a weak solution of sulphuric acid is put between the zinc and the membrane. By connecting several of these sustaining batteries together, a battery of considerable power will be formed, and which retains its energy for a long time. They may be connected so as to increase the intensity or the quantity.

We may here notice another delicate galvanoscope for detecting feeble currents, and depending on the principle of the experiment detailed in section 223. Instead of the wire there used, we employ Fig. 191. a thin strip of gold-leaf confined at both ends. It is covered by a glass to protect it from disturbances by wind, &c. When a current is sent through it, the action of the magnetism upon it makes the presence of the current manifest by a slight deflection of the gold strip.

THERMO-ELECTRICITY.

253. When two different metals, as copper and bismuth, are soldered together, and connected by wires to a multiplier, a powerful electric current becomes developed on heating the point of juncture of the two metals with a spirit lamp. If the multiplier be sufficiently delicate, the deviation of the needles will occur when the point of conjunction of both metals is grasped in the hand; a very slight elevation of temperature being sufficient to produce the effect. In general the most powerful currents are evolved by heating the more crystalline metals, as bismuth and antimony; and they increase within certain limits with the increase of temperature. The following list contains the names of several metals, any two of which being employed as a source of electricity, by heating them at their point of juncture, currents are developed in such a manner that each metal becomes positive to all below and negative to all above it in the list;

Bismuth,	Silver,
Platinum,	Copper,
Mercury,	Zinc,
Lead,	Iron,
Tin,	Antimony.
Gold,	

Different experimenters are not agreed as to the order in which these various metals should be arranged. The discrepancies, however, which have sometimes been manifested in the results, are probably attributable to the diversities which take place in the direction of the current when the metals contain an alloy, or are not in a state

of perfect purity. Thus, although bismuth and tin are each positive in regard to copper, yet an alloy of the two former is found to be negative in regard to the latter metal. German silver which is a mixture of copper, zinc, and nickel, is positive to all the metals with which it has been tried with the exception of bismuth, and in connexion with antimony forms a better thermo-electric pair than bismuth and antimony, which stand at the extreme positive and negative ends of the preceding list.

It is by no means necessary to employ two metals in these experiments or to solder them at the point of juncture; for if two pieces of copper wire be twisted together, and connected with the multiplier, a current of electricity takes place on holding a spirit lamp on one side of the juncture. Even platinum and gold wires will evolve these currents; so that they are to be regarded as arising from a series of decompositions and recompositions of electricity produced by the action of heat, and not necessarily resulting from oxidation or other chemical action. Becquerel found that the results remained the same when the experiments were performed in an atmosphere of hydrogen gas. In explaining therefore, this new form of electricity, he starts upon the hypothesis that, whenever a particle of a metal receives heat from a body of a higher temperature than itself, part of the neutral electric fluid which is attached to it is decomposed, the vitreous fluid being retained, and the resinous fluid being driven off, and passing into the adjoining particles of metal. In proportion as the heat extends by communication from particle to particle, similar effects take place in each of these that are acquiring heat, while contrary effects are taking place in all those that are losing heat. Thus, the simple diffusion of that portion of heat which was originally received by the first particle produces only an oscillating movement of the electrical fluid between adjacent particles, attended by a series of decompositions and recompositions of the two electric fluids. But, if the source of heat be permanent, so that the temperature of the first particles which receive it be uniformly maintained, the retrograde movements of the decomposed electric fluids are prevented, and a *continued* current of each takes place in opposite directions; the negative electricity being impelled forward from the parts where the temperature continues high to those which continue to be lower, and a

positive current moving in the contrary direction. Hence, when a uniform bar of metal is heated at one end, the cold portions assume negative and the hot ones positive electricity. When two different metals are placed in contact, so as to constitute a circuit, the currents from the heated parts that are conjoined will be urged in opposite directions; but the strongest will prevail and the thermo-electric current actually observed is that which results, and of which the intensity is equal to the difference of the two that are simultaneously developed; hence the dependence of the current upon the two metals which constitute the thermo-electric element.

254. The great peculiarity which distinguishes thermo-electric currents from hydro-electricity or galvanism, is that the *quantity* of circulating electricity is much greater compared with its *intensity*. In this respect, they are eminently distinguished from common machine electricity, the tension of which is very high, though the quantity is inferior to that which flows in voltaic combinations. It is very important, therefore, to furnish the best and shortest conductors to the thermo-electric current. They have not sufficient intensity to force their way through long conducting wires; it will be found of great service to divide the multiplier into several strands of thick and soft copper wire, and attach the ends of each directly with the battery, so as to shorten the circuit. For similar reasons, it is found to be no great advantage to form the metals into a very great compound circuit on account of the loss arising from the corresponding increase in the line of conductors. The total effect is much less than the sum of the effects which the pairs would produce separately, so that the forces increase in a much lower ratio than the number of alternations constituting the series. We might suppose from what has been said that this new form of electricity would first show itself by those effects which require the least intensity; such as the deflection of the magnetic needle, and the contractions in the limbs of a fresh frog; the former constituting the most delicate galvanoscope, and
Fig. 192. the latter a highly sensitive electroscope. If we hang upon the two poles of a horse-shoe magnet, compound rectangular frames, made of platinum, and silver wire, delicately balanced on pivots resting in agate cups, set in the ends *NS* of a magnet, and then apply a spirit lamp, so as to heat the corners where the two metals join, a thermo-electric will flow through these closed circuits, and the action

of the poles upon it will cause a rotation of from thirty to sixty turns in a minute. The motion around the two poles will be in opposite directions. A better arrangement is to hang a single set of wires on a pivot coming up from *A* to the level of the ends of the magnet, so as to allow both poles to act upon it. In this case, a stand may be placed for the lamp in front of *A*.

When a thermo-electric series is made of a large number of pairs, for the sake of compactness the wires may be placed side by side, Fig. 19
and then soldered at their ends, being insulated from one another, where they cross, by paper. Betto, of Turin, has succeeded in decomposing water and various saline solutions by a large number of alternations of platina and iron. In 1836, Antinori of Florence, by connecting a thermo-electric battery with a helix of insulated copper wire about five hundred feet in length, obtained on breaking contact a vivid spark from the induced or secondary current, produced by the passage of the primary thermo-electric current. Professor Wheatstone has repeated this experiment with thirty-three pairs of bismuth and antimony, formed into a cylindrical bundle 1.2 inches long and 0.75 inch diameter, using a coil of insulated copper ribbon, 1.5 inch broad and 50 feet long. Mr. Watkins has since obtained the same result with a single pair of the same metals, each being 0.5 inch long and 0.12 inch thick, and weighing only five grains. The same experimenter with a thermo-electric battery of thirty pairs, each plate being 1.5 inch square and 0.33 inch thick, and heating one end of the arrangement with a hot iron, whilst the other was kept cool with ice, succeeded in exciting an electro-magnet to such an extent as to support a weight of ninety-eight pounds. He has also heated a wire by thermo-electricity. Dr. Andrews, of Belfast, has discovered that platina wires, connected with a multiplier and plunged into fused salts, are traversed by an electric current. This may be shown by connecting a piece of platina wire with one screw of the multiplier, and bending its free end into a loop. On fusing a little borax in the loop, by means of the blow-pipe, and quickly inserting the previously *heated* end of a second platina wire, also connected with the multiplier into the fused bend, the needles flow to the extreme of the scale from the development of a powerful current. The direction of the positive current appears to be from the hot platina wire through the fused salt to the cold wire. By means

of these curious thermo-electric currents, Dr. Andrews succeeded in obtaining distinct evidence of chemical decomposition. The same results were obtained with several other fused salts. Recent experiments with large series have increased the confidence in the attempts to multiply this kind of electricity. A battery of thirty-six pairs has been constructed of such delicacy that the galvanoscope was affected by the current produced in it by the warmth of a person at the distance of thirty feet. Pressing the metals in the hand produces a great deflection of the needle. The apparatus, therefore, has been used successfully in experiments on the permeability of bodies to radiate heat, on the temperature of insects, and on the various degrees in which bodies possess the powers of emitting, reflecting, and absorbing heat, and to the measurement of heat in different parts of the animal system.

ANIMAL ELECTRICITY.

255. Certain fishes have, from remote antiquity, been well known to possess the property of communicating a numbing sensation to persons who have incautiously grasped them. This remarkable effect, whose intensity is sometimes so great as to amount to a severe shock, has been most satisfactorily traced to electricity; and no real difference exists between the electric fluid thus *secreted, or excited* by these animals, and any of the other modifications of that curious form of imponderable matter already described. The fishes hitherto met with, which possess this extraordinary faculty, are but few: of these the torpedo ocellata and marmorata are alone met with in Europe. The others, including the gymnotus, tetraodon, silurus, rhinobatus, and trichiurus electricus, are confined to the tropics. The torpedo, gymnotus, and silurus have been submitted to very careful investigation.

The electric organs of the torpedo lie on each side of the head and branchiæ; being made up of numerous five or six sided prisms, placed in such a manner as to present their bases to one surface of the fish, and their apices to the other; Hunter counted 1182 of them in a single organ. They are divided horizontally, by numerous septa, the interspaces being filled up with a gelatinous fluid. These organs are copiously supplied with nerves, which are chiefly branches of the par vagum, or pneumo-gastric nerves. The power of communicating the shock depends upon the integrity of the nerves, for the heart may be cut out and the animal flayed, without its losing this faculty; but as soon as the nerves are divided it vanishes entirely. The intensity of the shocks are increased by irritating

the organ of the electric nerves with the point of a knife. The electric discharge is directed from one surface of the fish to the other, the electricity of the dorsal surface being positive, and that of the ventral negative; and no shock is experienced unless direct, or indirect communication is made between the belly and back of the animal. A complete separation of the two electricities on the two surfaces does not occur, as that portion of the animal nearest the electric organs is positive, or negative, according to the particular surface, with respect to those parts nearer the tail. Dr. Davy succeeded in decomposing acidulated water, and iodide of potassium, as well as of heating but not igniting platina wire, and of magnetizing needles placed in a spiral coil of wire, by means of currents from the torpedo.

In the gymnotus, the electric organs are double, and extend on each side from the head to the tail. They are each formed of long horizontal membranous structures, placed at a short distance from each other, provided with numerous transverse septa, and filled, as in the torpedo, with a gelatinous fluid. These organs are supplied by spinal nerves, in which respect it differs from the last described fish; these consist of 224 pairs of intercostal nerves.

The gymnotus resembles an eel in appearance, and is often four and five feet in length; its shock is extremely strong and capable of paralyzing horses and mules. Walsh and Ingenhouss, in 1776, observed a spark to pass between two pieces of tinfoil through which the discharge of this eel was transmitted. This was doubted until, in 1836, the power possessed by electric fishes of yielding a spark was again asserted by Linari; and within the last year this statement has been placed beyond a doubt by the researches of Faraday, who, availing himself of the electric eel publicly exhibited at the Adelaide Gallery, succeeded in obtaining a current of sparks, and all those effects which are characteristic of ordinary voltaic electricity.

This remarkable fish died on the 14th of February, 1842. For a week previous, it became very inactive, and this inactivity increased to torpor. The cause of its death was mortification. It was carried to Paris from one of the many tributary streams of the river of the Amazons, about four years ago, and was the only one of its kind in Europe. Its structure was very singular. The seat of

the electric power lay between the shoulder and the tail, and between the head and the shoulder. Its food was small fish, which it could stun and stupefy by an electric shock, at two feet distance. It always stunned and stupefied these fish before it ate them. The most interesting and beautiful experiment performed by its electricity was in setting fire to a piece of silver paper in a glass cylinder. One end of a conductor was attached to the paper, and the other to the eel, and by this means the paper was burnt. It was necessary that the eel should be irritated before it would send forth electricity. It was young when first carried to Paris, and was blind for some time before its death.

The silurus is still less known than the gymnotus; its electric organs are, as in that fish, double, and are separated by a tough aponeurotic membrane; the most external of these organs lies immediately under the skin, the deeper one being imbedded in the muscles. They are both divided into cells; their nerves are, it is remarkable, the same as in both the torpedo and gymnotus, one of the organs being supplied by the pneumo-gastric, the other by the intercostal nerves.

256. In the electric fishes the power of *secreting* electricity resides in a particular structure; but a remnant of this power is observed in certain animals, especially among the *batrachians*, in which no supplementary organ of this kind is to be met with. At least, such a trace of a power of disturbing the electric equilibrium of the system, appears to reside in frogs and other animals, characterized by an intense degree of irritability to the stimulus of electricity. When frogs are used for this purpose, they should be employed in the spring, when they possess their highest degree of irritability; and *prepared*, by removing the skin from the legs and thighs, cutting them off from the body, and leaving as large a portion as possible of the sciatic nerves projecting.

Place the prepared legs of a frog on the table, holding a piece of zinc in one hand, bring the metal in contact with the sciatic nerves, and with the finger of the other hand touch the muscles of the leg; immediately a violent contraction will ensue.

If this experiment be repeated with a piece of iron, instead of a piece of zinc, the same contraction will occur; and to the accidental observance of this fact by Galvani, professor of anatomy at Bo-

logna, in 1790, we owe the discovery of galvanic and voltaic electricity.

It was, in opposing the theory proposed by Galvani, who supposed the electricity to be evolved by the vital functions of the animal, that Volta was led to make those great discoveries that led to the knowledge of that important science which so deservedly bears his name.

A far more satisfactory experiment, as proving the development of electricity in frogs — at least if the production of muscular contraction can be considered as conclusive on that point — is to place the prepared leg of a frog on a glass plate with the nerve hanging down. By means of a piece of wood, or glass, bring the truncated end of the nerve in contact with the muscles of the leg, and an immediate contraction of the latter will occur, if the frog has been lately killed, and possesses its usual irritability. Müller found that the same thing occurred when the nerve and the muscle were connected, by means of a dead or living frog, or even by a putrescent limb of one of those animals. This experiment generally succeeds best if performed on a frog just before the spawning season.

257. Among invertebrate animals, a few have been stated to have claims to be considered as electrical, but this is extremely doubtful. Molina relates that a certain Chilian spider possesses the property of benumbing the hand of the person who touches it. Kirby and Spence mention a species of cimex, the *reduvius serratus*, as having the power of communicating electric shocks. An account is on record also, of one of the great marine annelidæ, *leonice gigantea*, giving a powerful shock to the person who touched it.

258. With regard to the presence of electric currents circulating in warm-blooded animals, evidence is by no means so satisfactory, as in the case of animals of lower organization ; a solitary instance is on record by Cotugno of Milan, of a case in which shocks were given by a mouse dissected alive. Aldini, the nephew of Galvani, succeeded in producing contractions in decapitated animals, merely by communicating their nerves and muscles by means of his own body ; but these researches have not been repeated, and much obscurity still shrouds the whole subject. From some very late experiments of Matteuci, it appears tolerably certain that electric currents, capable of being detected by the multiplier, exist between the

liver and stomach of newly-killed animals ; these currents disappear entirely, on dividing the spinal marrow. Dr. Donné found that by placing a plate of platina in connexion with the multiplier, on the surface of the skin, and a second also communicating with that instrument in the mouth, the needles moved, from the existence of a positive current, passing from the moist cutaneous surface to the lining membrane of the mouth.

Pouillet fancied that he had succeeded in detecting free electricity circulating in the nerves, but his experiments are inconclusive. Very lately, Professor Prevost has stated, that by transfixing a nerve with a steel needle, and irritating the animal so as to cause contraction of the limb, the needle becomes magnetic by the consequent electric discharge. Still further researches are required before this statement can be regarded as beyond doubt.

259. Many persons, with Hunter, Abernethy, Proschasca, &c., have felt inclined to regard electricity as the cause of most, or all of the functions of life ; but no one has carried this to such an extravagant length as Meissner. This philosopher has asserted that, during respiration, blood acquires electricity, which becomes distributed by the pneumo-gastric and sympathetic nerves to the great nervous centres. Thus becoming charged, the brain excites the action of any organ by giving a spark to the nerve supplying that structure. The electric fluid thus sent to the muscles forms around each of their molecules a kind of atmosphere ; thus becoming similarly electrified, the fibres repel each other, separating in the middle of the muscle, and approximating their ends in a similar manner as in the experiment of the electric threads. This theory beautifully illustrates the well-known remark of Cicero, " that nothing can be imagined so absurd, as not to find a supporter among philosophers."

It is quite indisputable that the human body is always in an electric state, but of the feeblest tension, never exceeding that evolved by the contact of a plate of zinc with one of copper. It increases with the irritability of the person, and appears to be greater in the evening than in the morning, disappearing altogether in very cold weather. Pfaff and Ahrens, to whom we owe most of these observations, have also observed the electricity to be increased after partaking of spirituous potations, and to be generally positive.

Women are stated to be not unfrequently negative, especially during pregnancy. Hemmer, a German philosopher, in 2422 experiments on himself, found his electricity to be in 1252 trials positive, in 771 negative, and in 399 he could not detect a trace of free electricity.

260. Various accounts are on record of a large accumulation of electricity taking place in the human body, to the great inconvenience of the person possessing this peculiar property; but on investigating such reports, they may generally be traced to disturbance of electric equilibrium by friction, or other causes. Thus Cardan relates the case of a Carmelite monk, whose hair emitted sparks whenever it was stroked backwards; in which there is nothing very wonderful, for if the hair be dry, any one, especially in frosty weather, by drawing a comb through it in a dark room, will observe a plentiful evolution of sparks. Even in very unfavorable weather, if a person stands on an insulated stool and connects himself with a condenser connected with an electrometer and any one standing on the floor draws a comb rapidly through his hair, the gold leaves of the electrometer will diverge to their utmost extent, on drawing back the uninsulated plate of the condenser. In this experiment, by the act of drawing the comb through the hair, electric equilibrium is disturbed, the body being left in a positive state, the comb taking the free negative electricity.

Fire is said to have streamed during sleep from the head of the Roman King Servius Tullius; and a late writer has suggested that the flame related by Virgil to have played round the head of Ascanius, was electric; although perhaps the whole story was a poetical fabrication.

> Ecce levis summo de vertice visus Juli
> Fundere lumen apex, tractuque innoxia molli
> Lambere flamma comas, et circum tempora pasci.
>
> ÆNEID, ii. 628.

261. The vital functions of vegetables appear to be frequently attended with a disturbance of electric equilibrium, sufficient to evolve even sparks, at least if we are to believe reports on this subject. Pouillet has satisfactorily proved that electricity is evolved during germination, and Dr. Donné has shown that electric currents are to be detected in all ripe fruit, passing between their bases and apices.

From a few observations made by Dr. Bird on this subject, he arrived at the following conclusions:

1. The great improbability of vegetables, on account of their feeble insulation, even becoming so charged with electricity as to afford a spark, and the probability of those luminous phenomena said to be exhibited by some plants, depending on other sources than electric currents.

2. That electric currents *of very feeble tension* are always circulating in, and exerting their influence upon, vegetable tissues in every stage of their development.

3. That electric currents are developed during germination, and assist in producing the important chemical changes proper to that process; and that by causing the seed to assume an oppositely electric state, we retard or check its development.

Identity of the Electricity derived from different Sources.

262. The identity of the electricity derived from different sources is a subject which properly claims our notice at the close of a treatise upon the different forms under which the electrical, the magnetical, and the electro-magnetical phenomena are exhibited. But the new theory which we have just described, which refers the magnetic phenomena to electricity, and the mutual action of magnets and conductors to the mutual action of different conductors, appeals to this identity of voltaic and magneto-electricity as one link in the chain by which it is itself supported. We shall generalize the case, however, a little farther, and consider it as referring to the five different sources whence electricity may be drawn, viz.:

I. Ordinary Electricity, or Machine Electricity.
II. Voltaic Electricity.
III. Magneto-Electricity.
IV. Thermo-Electricity; and
V. Animal Electricity.

Faraday, in his experimental researches in Electricity, &c. was led to the discussion of this point, and he brought to the subject powers of observation, and delicacy and fulness of experimental

illustration, wholly unrivalled. We shall only attempt to give the principal results of his able communications on this subject. Many years ago, Cavendish, Wollaston, Colladon and others removed in succession some of the palpable objections to the identity of common, animal and voltaic electricity, and at the present day most philosophers concur in believing these to be the same. On the other hand, it is true that the accuracy of some of Wollaston's experiments has been denied, and the legitimate inference from others has been mistaken. Some philosophers still doubt the identity. Not only Sir Humphrey Davy, but Dr. Davy his brother, in a comparatively recent communication in the Philosophical Transactions of the Royal Society, have pressed these differences in the effects of electricity derived from different sources. For these reasons the subject seemed to Faraday worthy of a complete examination, extending to the five different sources of electricity named above. If the effects which all of these electricities are capable of producing, can be shown to be the same in kind, however various in degree, then the identity in dispute will be fairly established. Now these effects are reducible to six chief heads;—1. Electrical attraction and repulsion, which is particularly seen in electricity of tension, or statical electricity; 2d. Evolution of Heat; 3d. Magnetism; 4th. Chemical Decomposition; 5th. Physiological phenomena; 6th. Spark. Now the comparison of the several electricities requires that we should take up each of the five different kinds already named, and examine it in reference to these six points. And first, if we begin with machine electricity, all the six classes of phenomena, excepting the fourth, we have already had occasion to mention: the decomposing power was shown by Faraday through contrivances of his own, and the electricity of tension was made to resemble still more electricity in motion, by sending the charge from the machine through long and imperfect conductors. If we pass to voltaic electricity, we have anticipated the discussion, except so far as concerns the phenomena depending on high tension. The tension of this kind of electricity is low, so that the attractions and repulsions are weak; but still with a battery of one hundred pairs they are sufficient to move the gold leaf electroscope. Magneto-Electricity comes next; the only action to which we have not referred, in the chapter on the magneto-electric machines, is that of tension; and this also

has been obtained by careful experiments with the gold leaf electroscope.

Thermo-electricity and Animal Electricity, while they distinctly manifested the magnetic and physiological phenomena, and the latter also the power of chemical decomposition, have failed till very recently in producing those effects which depend upon a considerable degree of intensity. At the present moment, however, all the deficiencies, with two exceptions, have been supplied. Thermo-electricity and animal electricity have not yet produced the statical attractions and repulsions; which belong peculiarly to electricity of very high tension. Out of thirty points of comparison therefore, there are twenty-eight cases which prove the identity of the variously derived electricities, and only two at fault; and these cases are peculiar and can be satisfactorily explained. As we know nothing of any of these electricities except their properties, and as we find the same properties to be possessed by all in various degrees, we cannot resist the conclusion that they are all identical in their nature. This difference of degree of which we speak makes no change in the conclusion to be deduced from the facts; for the same difference may be artificially produced in electricity coming from the same source, without destroying its identity. Some of the characteristic phenomena may be exalted, while others are diminished, without causing a doubt whether the essential character remains the same. In voltaic electricity, we are obliged to recognise distinctions of this sort; and the difference, in effect, of quantity and intensity currents is equal to any change of phenomena that is observed when we pass from one source of electricity to another.

[illegible]

NOTES.

I.

The Torsion Balance.

After a careful analysis of the effect of torsion in the case of wires, Coulomb made a very happy application of this principle to the construction of an instrument for the purpose of measuring all kinds of small forces. This instrument consists principally of a vertical wire, the upper end of which is attached to a fixed point, and the lower end, kept steady by a small weight, carries a horizontal needle. When we would estimate very small forces, we bring them to act upon the extremity of this needle, and measure their intensity by the angle through which they cause it to diverge from its point at rest. In a word, we *balance* the force in question by the torsion of the wire; and it is for this reason, that Coulomb has given to this instrument the name of *torsion balance.*

To prevent the needle from being agitated by the air, it is enclosed in a cylindrical glass case; and the wire is likewise enclosed in a hollow glass cylinder, at the top of which is placed a graduated circle, which turns with considerable friction about the cylinder. The stem to which the wire is attached, carries a horizontal index, which moves over this circle, and serves to point out the number of degrees, when we wish to give the wire a determinate torsion. There is likewise a circular division applied horizontally about the glass case to measure the range of the needle.

We give the wire and needle different lengths and magnitudes, depending upon the object we have in view. If the forces we wish to measure are very small, in which case the instrument must have great sensibility, we use long and fine wires; for the force of torsion is inversely as the length of the wire, and directly as the fourth power of its thickness. Long wires have this advantage also, that we can twist them through a greater number of degrees without changing the law of their elasticity. It is necessary, moreover, to use those substances whose elasticity is most perfect.

The torsion balance will serve to render sensible the universal attraction, which takes place between all bodies in nature, in the direct ratio of their masses, and in the inverse ratio of the squares of their distances, and by virtue of which, under the name of gravity, all bodies around us tend towards the centre of the earth. Suppose the needle to be at rest, in a position determined by the natural state of the wire, and that two spheres, of any substance whatever, are brought toward the extremities of the needle on opposite sides. If they really exert an attraction at a distance upon the particles of the needle thus suspended, and if they are attracted in turn by the needle, the needle must be moved from its original position; and its extremities must approach the spheres which attract it, until the force of torsion of the wire, which opposes this motion, is sufficient to counterbalance the attraction. The needle will not stop, however, at the precise instant when this equilibrium takes place, but will continue to move, not in virtue of the attraction, but in consequence of its velocity previously acquired. It will, therefore, advance until the force of torsion, always increasing, destroys this velocity and begins to bring the needle back to its position of rest; it then passes this point to a certain distance on the other side, after which it begins again to move towards the spheres; and thus it will perform a series of oscillations. The effect may be rendered more sensible by giving the needle such a form, that the greater part of its mass shall be situated towards its extremities; which will be the case, if we use a cylindrical needle, terminated at each end by a ball of a considerable diameter compared with that of the cylinder. This will have the additional advantage of facilitating the calculation; for among the laws of attraction it is shown, that a homogeneous sphere acts upon a point situated without it, as if its whole mass were united in a single point at its centre; and, although the mass of the needle can never be rendered absolutely nothing, yet it is manifest, that, if it be very small compared with the mass of the spheres which terminate it, its influence must be proportionally feeble, and may be easily allowed for. We are able then to obtain, by the laws of mechanics, an expression for the forces which attract the two spheres, when they oscillate with the observed velocity, in the presence of attracting bodies, which may also, for the sake of simplicity, be considered as spherical. If we compare the duration of these oscillations with the durations of the oscillations of a vertical pendulum, produced by the action of the terrestrial globe, we shall have the ratio between this force and that of the spheres in question; hence, we deduce the ratios between the masses of these bodies and the mass of earth; and, as the bulks of these bodies are supposed to be known, we shall obtain the ratios of their densities. Cavendish, who made this fine experiment, found, in the way we have stated, the mean density of the earth, that of water being unity, to be 5,5.

Coulomb applied the torsion balance to the purpose of measuring the intensities of electric and magnetic forces. He even used it to

ascertain the adhesive force of liquids, considered with respect to themselves and to other bodies. For this purpose, he immersed in the liquids, plane discs, suspended by their centres in a horizontal position by means of wires of a known force, and he compared together the velocities of the oscillations performed by these discs in the liquids and in the air.

II.

Instructions respecting the best Form, &c. of Lightning Rods.

The most advantageous form that can be given to lightning-rods, appears evidently to be that of a very sharp cone; and the higher it is elevated in the air, other circumstances being the same, the more its efficacy will be increased, as is clearly proved by the experiments with electrical kites, made by MM. de Romas and Charles.

It has not been accurately ascertained, how far the sphere of action of a lightning-rod extends; but, in several instances, the more remote parts of large buildings on which they have been erected, have been struck by lightning at the distance of three or four times the length of the conductor from the rod. It is calculated by M. Charles, that a lightning-rod will effectually protect a circular space, whose radius is twice the height of the conductor; and they are now attached to buildings according to this principle.

A current of electric matter, whether luminous or not, is always accompanied by heat, the intensity of which depends on the velocity of the current. This heat is sufficient to make a wire red-hot, or to fuse or disperse it, if sufficiently slender; but it scarcely raises the temperature of a bar of metal, on account of its large mass. It is by the heat of the electric current, as well as by that disengaged from the air, condensed by the passage of the lightning through it, when not conveyed by a good conductor, that buildings struck by it are frequently set on fire.

No instance has yet occurred of an iron bar, of rather more than half an inch square, or of a cylinder of the same diameter, having been fused, or even heated red-hot by lightning. A bar of this size would therefore be sufficient for a lightning-rod; but, as its stem ought to rise from 15 to 20 feet above the building, it would not be strong enough to resist the action of the wind, unless the lower part were made much thicker.

An iron bar, about three-quarters of an inch square, is sufficient for conductors. It might even be made still smaller, and consist merely of a wire, provided it be connected at the surface of the ground with a bar of metal, about half an inch square, immersed in water, or a moist soil. The wire, indeed, would pretty certainly be dispersed by the lightning, but it would direct it to the ground, and protect the surrounding objects from the stroke. However, it is always better to

make the conductor so large as not to be destroyed by the stroke: and the only motive for substituting a wire for a stout bar is the saving in point of expense.

The noise of the thunder generally occasions much alarm, although the danger is then passed; it is over, indeed, on the appearance of the lightning, for any one struck by it neither sees the flash, nor hears the report. The noise is never heard till after the flash, and its distance may be estimated at so many times 1136 feet as there are seconds between the appearance of the lightning and the sound of the thunder.

Lightning often strikes solitary trees; because, rising to a great height, and burying their roots deep in the soil, they are true lightning-rods, and they are often fatal to the individuals who seek them for shelter; since they do not convey the lightning with sufficient rapidity to the ground, and are worse conductors than men and animals. When the lightning reaches the foot of the tree, it divides itself amongst the neighboring conductors, or strikes some in preference to others, according to circumstances; and sometimes it has been known to kill every animal that had sought shelter under the tree; at others, only a single one out of many has perished by the stroke.

A lightning-rod, on the contrary, well connected with the ground, is a certain security against the effects of lightning, which will never leave it to strike a person at its foot; though it would not be prudent to station one's self close to it, for fear of some accidental break in the conductor, or of its not being in perfect communication with the ground.

When lightning strikes a house, it usually falls on the chimneys, either from their being the most elevated parts, or because they are lined with soot, which is a better conductor than dry wood, stone, or brick. The neighborhood of the fire-place is consequently the most insecure spot in a room during a thunderstorm. It is best to station one's self in a corner opposite the windows, at a distance from every article of iron or other metal of any considerable size.

Persons are often struck by lightning without being killed; and others have been wholly saved from injury by silk dresses, which serve to insulate the body, and prevent the access of the electric matter.

The stem, or part of the rod above the building, should be a square bar of iron, tapering from its base to the summit, in the form of a pyramid. For a height of from 20 to 30 feet, which is the mean length of the stems placed on large buildings, the base should be about 2½ inches square.

Iron being exposed to rust by the action of the air and moisture, the point of the stem is liable to become blunt; to prevent this, a portion is cut off from the upper end, about 20 inches in length, and replaced by a conical stem of brass or copper, gilt at its extremity, or

terminated by a small platina needle, two inches long.* The platina needle should be soldered with silver solder to the copper stem; and to prevent its separating from it, which might sometimes happen, notwithstanding the solder, it is secured by a small collar of copper. The copper stem is united to the iron one by means of a gudgeon which screws into each. If the gilding of the point cannot easily be performed on the spot, nor the platina readily obtained, they may both be dispensed with without any inconvenience, and a plain conical copper stem only be employed. Copper does not rust to any considerable depth in the air, and even if the point becomes somewhat blunt, the rod will not thereby lose its efficacy.

Below the stem, three inches from the roof, is a cap, soldered to the body of the stem, and intended to throw off the rain water, which would flow down the stem, and tend to injure the building.

Immediately above the cap, the stem is rounded for about two inches to receive a split collar, with a hinge and two ears, between which the extremity of the conductor of the lightning-rod is fixed by a bolt. Instead of the collar, we may make use of a square stirrup, embracing the stem closely. The stem of the lightning-rod is fixed on the roof of buildings, according to circumstances. If it is to be placed above a rafter, the ridge must be pierced with a hole through which the foot of the stem passes, and is steadily fixed against the king-post by means of several clamps. This disposition is very firm, and should be preferred if the circumstances admit of it.

If the stem be fixed on the ridge, a square hole must be made through it of the same dimensions as the foot of the stem; and above and below we fix, by means of bolts, or two bolted stirrups, which embrace and draw the ridge together, two iron plates about three-quarters of an inch thick, each having a hole corresponding to that in the wood work. The stem rests by a small collet on the upper plate, against which it is strongly pressed by a nut, made to screw on the end of the stem against the lower plate.

Lastly, if the lightning-rod is to be fixed on a vaulted roof, it should be terminated by three or four feet, or spurs, which must be soldered into the stone, with lead, in the usual manner.

The lower part of the conductor should be an iron bar or rod about three-quarters of an inch thick, reaching from the bottom of the stem to the ground. It should be firmly united to the stem by means of a collar, screw, or bolt, and its several parts should be connected together in a similar manner. After penetrating into the ground for about two feet, it should be bent at right angles to the wall of the building, and, after being carried in that direction for twelve or fifteen feet, it should be made to communicate with a well, drain, aqueduct, or permanently moist earth. If the soil be dry, it should extend to the depth of twelve or fifteen feet; and, to secure it from rust, it

* Instead of a platina needle, one of standard silver may be substituted, composed of nine parts of silver, and one of copper.

should be surrounded with charcoal, which is indestructible, and which, while it preserves the iron, facilitates the passage of the electricity into the ground by its conducting property.

Both the bottom and top of a lightning-rod are sometimes made to terminate in several branches, and its efficacy is thus increased. It is also recommended to connect with the lightning-rod any large masses of iron that may be in the building, as metal pipes, and gutters, iron braces, &c.; without this precaution the lightning might strike from the lightning-rod to the metal, especially if there happened to be any interruptions to the former, and thus occasion serious injury to the building, and danger to its inhabitants.

In the case of powder magazines, the lightning-rod should not be attached to the building, but to poles eight or ten feet from it. If the building be large, several should be used, arranged according to the rule, that *a lightning-rod may be considered as protecting a circular space whose radius is twice the height of the rod.* If the magazine be in a tower or other very lofty building, it may be sufficient to defend it by a double copper conductor, without any stem. As the influence of this conductor will not extend beyond the building, it cannot attract the lightning from a distance, and yet it will protect the magazine, should the lightning happen to fall upon it.

In the case of a vessel, the stem may consist merely of the copper point already described. It should be screwed on an iron rod, rising above the top-gallant mast, and connected by means of a hook or ring at its other extremity, with a metallic rope extending to the water or copper sheathing of the vessel. Large ships should be provided with two conductors, one on the main mast, and one on the mizen mast.

The experience of fifty years demonstrates, that, when constructed with the requisite care, lightning-rods effectually secure the buildings on which they are placed, from being injured by lightning. In the United States, where thunder-storms are more frequent and more formidable than they are in Europe, their use has become general; a great number of buildings have been struck,, and scarcely two are quoted as not having been saved from danger. The apprehension of the more frequent fall of lightning on buildings provided with lightning-rods, is unfounded, for their influence extends to too small a distance to justify the idea, that they determine the lightning of an electric cloud to discharge itself on the spot where they are erected. On the contrary, it appears certain, from observation, that buildings furnished with lightning-rods are not more frequently struck than formerly. Besides, the property of a lightning-rod to attract the lightning must also imply that of transmitting it freely to the ground, and hence no danger can arise as to the safety of the building.

We have recommended the use of sharp points for lightning-rods, as having an advantage over bars rounded at the extremity, by continually pouring off into the air, whilst under the influence of a thunder-cloud, a current of electric matter in a contrary state to that of the cloud, which must probably have some effect towards neutral-

izing the state of the latter. This advantage must by no means be neglected; for it is sufficient to know the power of points, and the experiments of M. Charles and M. Romas with a kite flown under a thunder-cloud, to be convinced, that, if sharp-pointed lightning-rods were placed in considerable numbers on lofty places, they would actually diminish the electric matter of the clouds, and the frequency of the fall of lightning on the surface of the earth. However, if the point of a conductor should be blunted by lightning, or any other cause, we are not to suppose, because it has lost the property we have mentioned, that it has also become ineffectual to protect the building. Dr. Rittenhouse relates, that having often examined the extremities of the lightning-rods in Philadelphia, where they are very general, with an excellent telescope, he observed many whose points had been fused; but he never found that the houses on which they were erected had in consequence been struck by lightning.

Dr. King and his successors in Boston have introduced greater care into the erection of lightning-rods, and have made some modifications in the shape and connexions, which are likely to prevent the accidents that have sometimes happened to buildings, supposed to be protected.

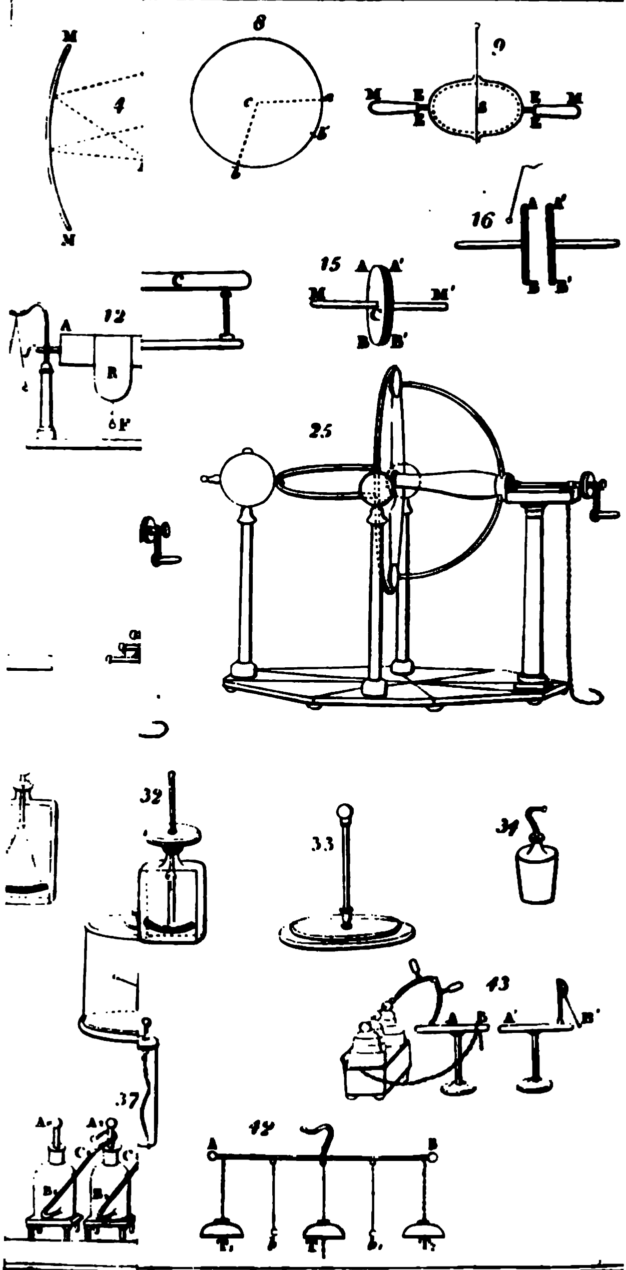
III.

Inclination of the Dipping-needle at London, &c. from the Time it was first observed.

Place.	Years.	Dip.		Observers.
London	1576	71°	30′	Norman.
——	1600	72	0	Gilbert.
——	1676	73	47	Bond.
——	1720	75	10	Wiston.
——	1723	75	0	Graham.
——	1772	72	19	Nairne.
——	1776	72	30	Cavendish.
——	1805	70	21	Gilpin.
——	1821	70	3	Sabine.
——	1836	69	17	——
Cambridge	1780	69	51	Williams
——	1782	69	41	——
——	1783	69	41	——
——	1840	74	21	Lovering

Declination of the Magnetic Needle at London, &c. from the Time it was first observed.

Place.	Years.	Declination.				Observers.
London	1580	11°	15′	0″	East	Barrows.
———	1622	6	0	0	———	Gunter.
———	1634	4	5	0	———	Gellibrand.
———	1657	0	0	0	———	Bond.
———	1672	2	30	0	West	Halley.
———	1682	4	30	0	———	———
———	1692	6	0	0	———	———
———	1722	14	20	0	———	Graham.
———	1747	17	40	0	———	———
———	1774	21	16	0	———	Cavendish.
———	1786	23	17	0	———	Gilpin.
———	1790	23	39	0	———	———
———	1796	24	0	0	———	———
———	1800	24	3	36	———	———
———	1809	24	11	0	———	———
———	1814	24	21	10	———	Lee.
———	1815	24	17	5	———	———
———	1816	24	17	54	———	———
———	1817	24	17	0	———	———
———	1818	24	15	43	———	———
———	1819	24	14	47	———	———
———	1820	24	11	44	———	———
———	1821	24	11	18	———	———
———	1822	24	9	55	———	———
———	1823	24	9	48	———	———
———	1836	24	0	0	———	Sabine.
Cambridge	1708	9	0	0	West	Brattle
———	1742	8	0	0	———	Winthrop
———	1757	7	20	0	———	———
———	1761	7	14	0	———	Williams
———	1763	7	0	0	———	Winthrop
———	1780	7	2	0	———	Williams
Beverly	1781	7	2	0	———	Willard
Cambridge	1782	6	46	0	———	Williams
———	1783	6	52	0	———	———
———	1788	6	38	0	———	———
Boston	1793	6	30	0	———	Vila
Salem	1805	5	57	0	———	Bowditch
———	1808	5	20	0	———	———
———	1810	6	22	0	———	———
Cambridge	1810	7	30	0	———	Farrar
———	1835	8	51	0	———	———
———	1840	9	18	0	———	Lovering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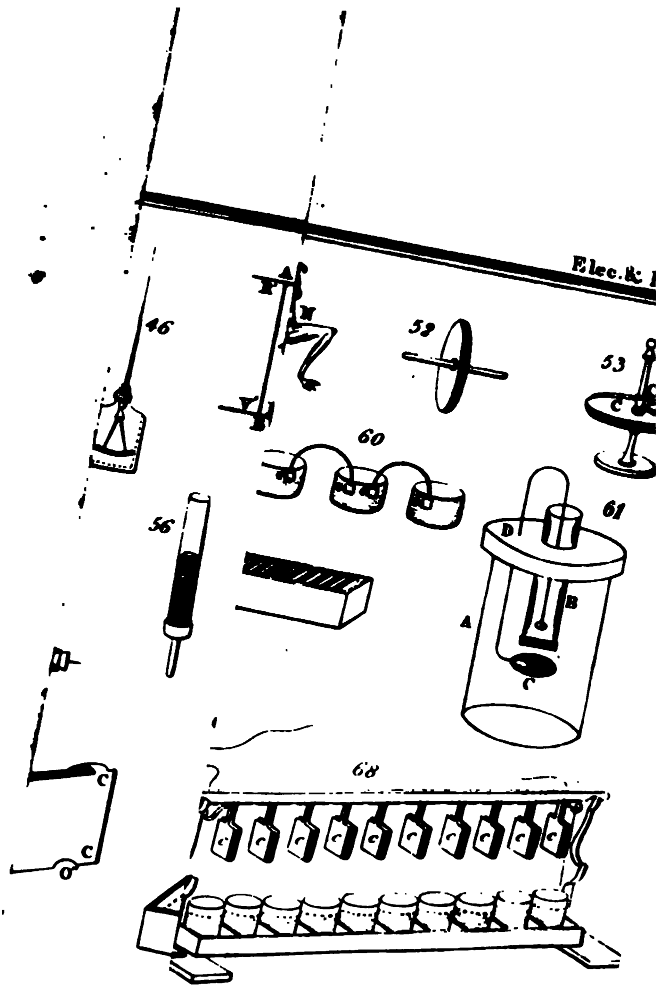
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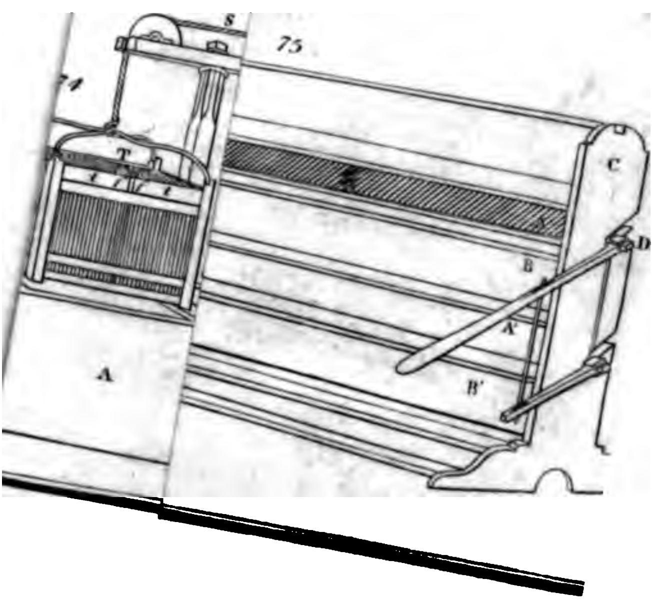
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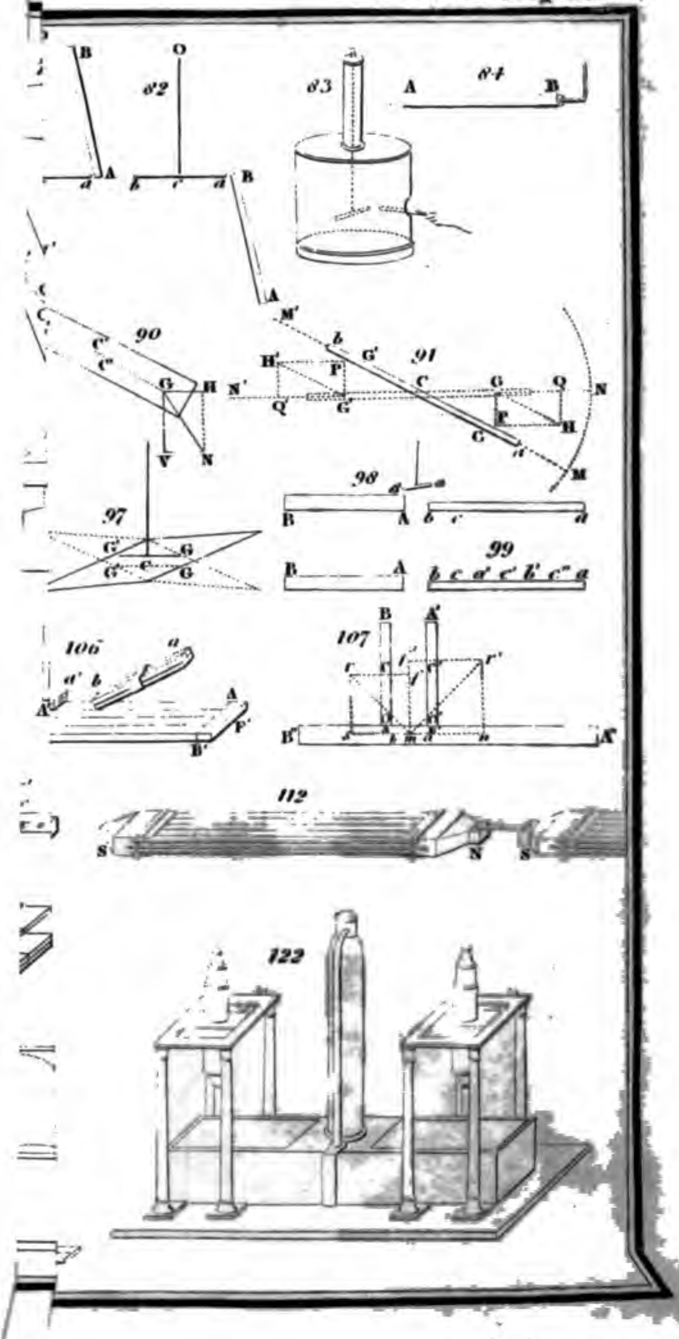
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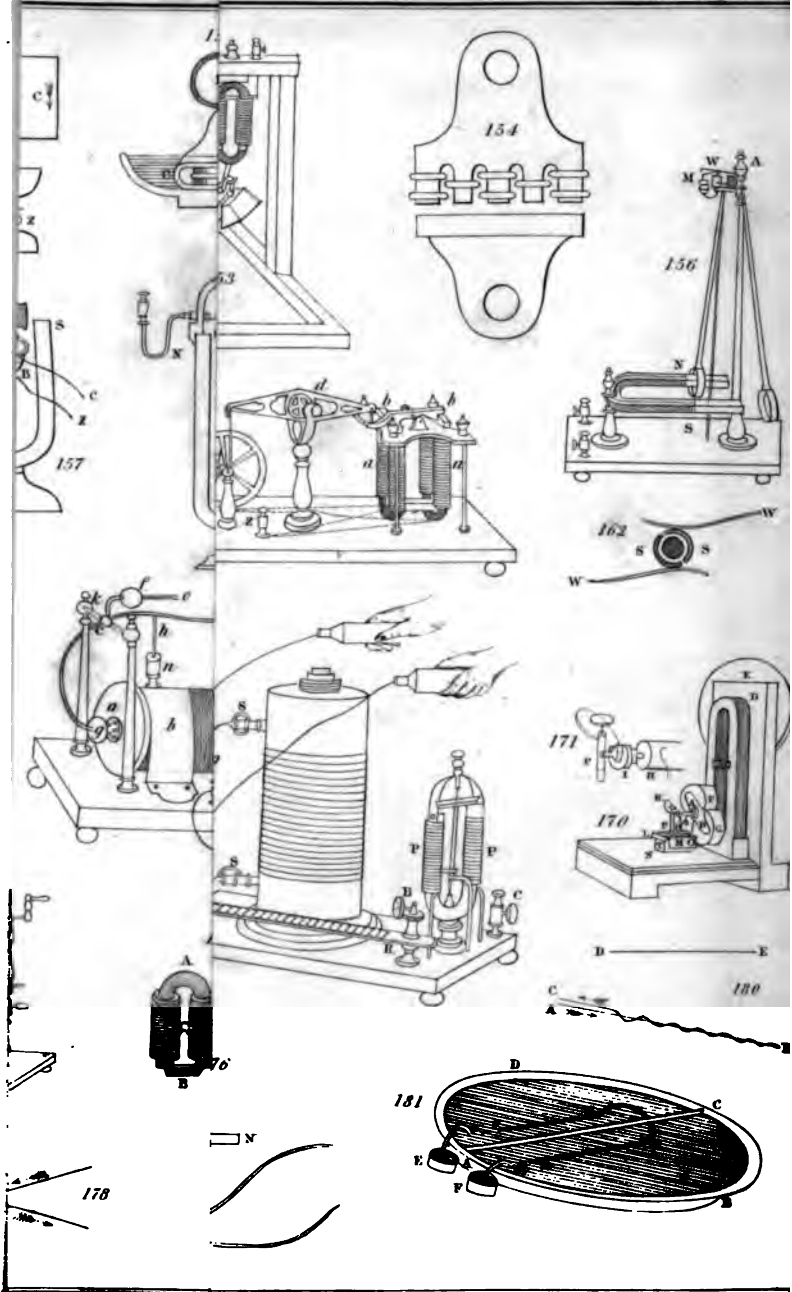
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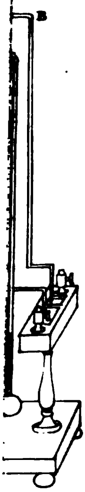

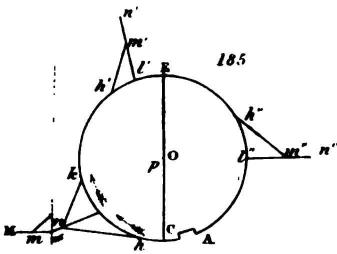

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